Technology
Development
Program Plan

VOLUME II–
Integrated
Technolog

The technology developed today is used in the science of tomorrow.

The Decade of Discovery in Astronomy and Astrophysics
National Research Council

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Abstract: In 1989 the Astrophysics Division of NASA Headquarters initiated AstroTech 21, a joint program of the Office of Advanced Concepts and Technology to lay the technological foundation for its scientific program for the 21st century. Recommended initiatives include: Space Infrared Telescope Facility (SIRTF); Stratospheric Observatory for Infrared Astronomy (SOFIA); Astrometric Interferometry Mission (AIDM0; optical and infrared interferometry in space; technology for the next generation observatories, including large telescope technoloy; submillimeter receiver and telescope technology; and high energy mirror and detector technology.

Descriptors, Keywords: AstroTech 21 mission implementation technology transfer continuous flight SOFIA explorer HST Hubble telescope instrument SIRTF SMIM/FIRST AIM lunar astrophysics relativity gravity radio astronomy spacecraft sensor optics interferometry

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AstroTech 21

Volume II

Integrated Technologies

Technology Development Program Plan

for the U.S. Space Astrophysics Program

by the Astrophysics-Technology Team

Astrophysics Division / Office of Advanced Concepts and Technology

NASA Headquarters

March 26, 1993

Contents

Volume II

NOTE CONCERNING BUDGET FIGURES CONTAINED IN THIS PLAN

The budget figures listed in this plan refer to the resource requirements to implement the described AstroTech 21 program.

The resource requirements referring to future years DO NOT necessarily reflect actual budgets that are contained within NASA's current plans.

Technology Planning and Needs for Future Astrophysics Missions

June 22, 1992

Mike Kaplan

Chief, Advanced Programs Branch

Astrophysics Division, NASA Headquarters

Presented to the Joint Committee on Technology for Space Science and Applications

Space Studies Board / Aeronautics and Space Engineering Board

National Research Council

Outline of Presentation

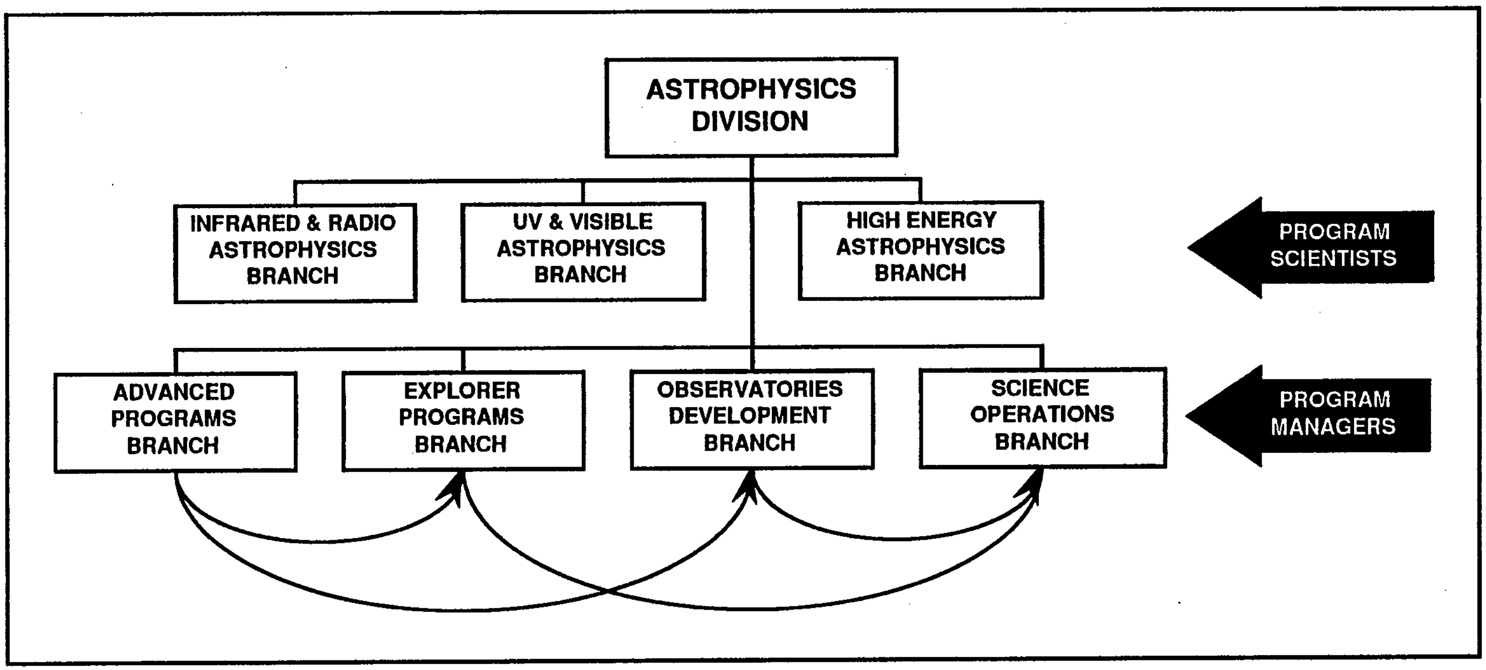
- Background
  - Goals
  - NAS Recommendations
    - Astronomy and Astrophysics Survey Committee Recommendations
  - Guiding Principles
  - Strategy for the Future
    - Astrophysics Strategic Plan
- Technology Planning
  - Planning Process
  - Astrotech 21
- Astrophysics Technology Needs and Priorities
- Comments on Technology Planning at NASA

Program Goals

Conduct a comprehensive exploration of the universe

- Themes:
  - **Astronomy**: What is the nature of planets, stars, and galaxies?
  - **Cosmology**: What are the origin and fate of the universe?
  - **Physics**: What are the laws of physics in the extreme conditions of astrophysical objects?

Organization of the Astrophysics Division



National Academy of Science Recommendations

NAS Recommendations

- Every decade, the NAS conducts a community-wide survey of future needs for **all** astronomy and astrophysics
- NRC commissioned the Astronomy & Astrophysics Survey Committee (AASC) to survey their field and recommend new ground- and space-based programs for the 1990's
- Survey Committee chaired by John Bahcall -- established 2/89
- Established 15 advisory panels to represent different wavelength subdisciplines + solar, planetary and laboratory astrophysics
- Comprised of over 300 astronomers & astrophysicists
  - More than 15% of all of the active astronomers in the US participated in this survey!!
- Report issued 3/91, **The Decade of Discovery in Astronomy and Astrophysics**

Bahcall Recommendations - Science

Space-based Priorities:

- **Large Programs:**
  1. SIRTF
- **Moderate Programs:**
  1. Dedicated spacecraft for FUSE
  2. SOFIA
  3. Delta-class Explorer acceleration
     - 6 astrophysics missions in the 90's, e.g., NAE/INTEGRAL and SMIM
  4. Astrometric Interferometry Mission (AIM)
  5. International collaboration on space instruments
- **Illustrative Small Programs:**
  1. Small Explorer acceleration
     - 5 astrophysics missions in the 90's
  2. Orbiting planetary telescope (Code SL)
  3. VSOP/RadioAstron
  4. Laboratory astrophysics

Bahcall Recommendations - Technology Development

Recommendations are not in priority order!!

Technology Initiatives

- Optical and infrared interferometry from space
- Technology for next-generation observatories
  - Large telescope technology
  - Submillimeter receiver and telescope technology
  - High-energy mirror and detector technology

Guiding Principles

Guiding Principles for the '90s

- Lead the opening of major scientific frontiers
- Pursue discoveries with specialized follow-on missions
- Provide frequent and rapid access to space
- Create opportunities for innovation
- Train the next generation of investigators
- Advance national education goals using the unique appeal of astronomy
- Invest in the future through basic research and technology development
- Produce, analyze and disseminate new knowledge efficiently
- Sponsor OSSA programs of exceptional merit

Lead the Opening of Major Scientific Frontiers

"NASA's goal of providing new windows to the universe, if successfully completed, will be among the most important organized intellectual efforts of the 20th century." *The Decade of Discovery, NAS*

Implementation: Space Infrared Telescope Facility (SIRTF)

- **Infrared Great Observatory directly addresses the most profound questions of modern astrophysics, for example**
  - How do planets, stars and galaxies form?
  - Are there planets around other stars?
- **Mission of enormous breadth**
  - Serves many astronomical disciplines including planetary science
  - Has broad community participation – 200-300 guest investigator teams/year
- **Great leap in technical capability**
  - Up to 10,000 times greater astronomical capability than any preceding or planned IR mission
  - A true observatory with an ensemble of imagers and spectrometers over a broad spectral range (1.8 - 1200 μm)
- **Highest priority mission for the 1990s for all astronomy (Decade of Discovery, NAS)**
- **Completes Great Observatories program**
  - Coverage of all spectral regions
  - Physical understanding through multispectral analysis

Pursue Discoveries with Specialized Follow-on Missions

"... the Committee believes that three areas of space astronomy are particularly primed for Delta-class experiments: gamma ray spectroscopy of galactic and extragalactic sources, a complete submillimeter line survey of important astronomical objects, and an x-ray telescope ..."

The Decade of Discovery, NAS

Implementation: Nuclear Astrophysics Experiment (NAE) and Submillimeter Intermediate Mission (SMIM)

- **Recent missions have opened new windows**
  - Gamma-ray sky revealed by GRO
  - Submillimeter region opened by IRAS and the Kuiper Airborne Observatory
- **Understanding discoveries requires specialized techniques**
  - Gamma ray high resolution spectroscopy using cooled germanium detectors
  - Submillimeter high-resolution spectroscopy using heterodyne spectrometers
- **Missions rated highest by peer review in broad multidisciplinary competition**
  - NAE is one of four missions selected for Phase A study in 1988
  - SMIM highest priority IR/Submm/Radio review panel for 1986 Explorer solicitation

Nuclear Astrophysics Experiment (NAE) / INTEGRAL

- **NAE is a intermediate mission**
  - Possible alternate: INTEGRAL, a cooperative ESA mission
- **New germanium technology provides simultaneous major advances in sensitivity and spectral resolution**
  - 100 times better ability to detect and resolve spectral lines
- **Probes matter in extreme conditions near neutron stars**
  - Positron production in star's magnetosphere
  - Magnetic fields through cyclotron resonances
  - High temperature plasmas in accretion disks
- **Reveals details about the creation of elements**
  - Direct measurement of heavy elements produced in the Galaxy over the past million years
  - Observations of explosive nucleosynthesis from supernovae out to the Virgo cluster

Note: INTEGRAL version also contains an ESA-supplied imager with 1 arc min identification of gamma-ray sources

Submillimeter Intermediate Mission

- **First spectral line survey of the full submillimeter band (100 - 750 μm)**
- **Reveals physical processes in cool objects (10 - 100 K): in cool objects, emission peaks at submillimeter wavelengths**
  - Solar System study of gases associated with comets, planets and satellites
  - Extra-solar system study of conditions within star and planet formation regions
- **Enhances our understanding of the structure and evolution of galaxies: submillimeter radiation penetrates interstellar gas and dust clouds**
  - Measures elemental abundance ratios in nearby galaxies
  - Reveals red-shifted distant galaxy emission through surrounding dust
- **Enabled by recent advances in technology**
  - Uses sensitive heterodyne receivers in 1.2 THz (250 μm)
  - Has a lightweight 2.5 m composite honeycomb primary reflector

Provide Frequent and Rapid Access to Space

"... this Committee has for years repeatedly advised on the need for frequent and rapid access to space ..."

SSAAC Statement, Small Missions Report, Feb. 1991

Implementation: Explorer Program

- **Redirect Explorer program to emphasize launch frequency**
  - Goal of launching three missions every year
  - Short development – three years or faster per mission
- **Provides flexibility through three types of missions:**
  - Middle-class Explorers: ~$65M ($ FY 92), 400-500 kg.
  - Small Explorers: ~$35M plus in-house support, 200-300 kg.
  - University Small Explorers: ~$30M, 200-300 kg.
- **Serves the disciplines in space physics and astrophysics**

Create Opportunities for Innovation

"We strongly encourage NASA to transfer as much authority and accountability to the Principal Investigator as possible."

SSAAC Statement, Small Missions Report, Feb. 1991

Implementation: University Small Explorer Program

- **The Principal Investigator (PI) has full authority and accountability over the total mission**
  - Define systems requirements and determine trade-offs
  - Allocate resources
  - Manage risk and quality assurance
- **Fosters innovative approaches in mission development**
- **Negotiated, the "fixed" budget – problems solved within defined resources**

Train the Next Generation of Investigators

"... it is essential to invest in the education and training of scientists, thereby creating a continuing source of scientific talent for space science for the nation."

SSAAC Statement, Feb. 1991

Implementation: Stratospheric Observatory for Infrared Astronomy (SOFIA)

- **Airborne observatory – Boeing 747 modified to fly a 2.5 meter telescope**
- **Provides 160 research flights per year for an estimated 65 science teams**
- **Instrument development time is well matched to a graduate student's career**
- **Facilitates rapid development of high-risk, high-payoff IR and submillimeter technology**
  - Provides the capability for real-time fixes and adjustments to instruments
  - Enhances testing and modification through frequent and timely re-flights
- **High spatial and spectral resolution complements SIRTF's exquisite sensitivity**
  - Diffraction limited at wavelengths longer than 15 μm
  - Spectral resolving power at 10 using heterodyne techniques

Advance National Education Goals Using the Unique Appeal of Astronomy

"... astronomy has a special appeal to young people and is particularly effective in stimulating interest in science and engineering at an early age ..." *The Decade of Discovery, NAS*

Implementation: Initiative to Develop Education through Astronomy (IDEA)

- **Facilitate interaction between astronomers and pre-collegiate/public education**
  - Grant supplements – augmentations to current grants for use in pre-collegiate or public education programs
  - Hubble Space Telescope Outreach Program – wide HST visibility makes it ideal for use in stimulating interest in science
  - KAO/SOFIA Adopt-a-Classroom – Fly teachers for "hands-on" experience
- **Expected benefits**
  - Motivate students to pursue careers in science and engineering
  - Enhance mathematical, technological and scientific literacy of all Americans

Invest in the Future Through Basic Research and Technology Development

"The technology developed today is the science of tomorrow."

The Decade of Discovery, NAS

Implementation: Research and Analysis Program

- **Grants to the science community provide the foundation for flight programs**
  - Balanced program of theory, laboratory astrophysics and instrument development
  - Over 200 peer-reviewed funding actions to university- and NASA center-based community
- **Advanced Technology Development (ATD) provides for concept definition and technology development for future missions**
  - Critical for all missions from Explorers through larger missions, e.g., NAE, SMIM, AIM, SIRTF, and "Greater Observatories"
  - Current technology development is focused on interferometry, large telescope optics, submillimeter receivers, and high energy detectors and optics
  - Preparation for Mission From Planet Earth is at a pace and scope commensurate with national commitments – early focus on the Lunar Transit Telescope LTT)

Produce, Analyze and Disseminate New Knowledge Efficiently

"In the three complementary areas of digital data handling, intensive data processing and theoretical modeling, astronomers are ready to take advantage of the expected technological advances of the 1990s ..."

The Decade of Discovery, NAS

Implementation: Mission Operations and Data Analysis (MO&DA)Program

- **Contains the essence of all astrophysics missions – to obtain new scientific understanding of astrophysical phenomena**
- **Vital to all phases of the analysis cycle: conduct operations, analyze data, interpret findings, and disseminate results**
- **Facilities panchromatic analysis**
  - Operate missions and archive data at centers of expertise
  - Distribute data using the Astrophysics Data System
- **Emphasizes the guest investigator programs**
  - Nearly 1,000 investigators are presently participating in observing and archival research programs

Sponsor OSSA Programs of Exceptional Merit

"By any reasonable measure, general relativity has been subjected to comparatively few tests and, despite the fact that it has passed every one of them, it is still badly in need of further, independent verification."

1991 Gravity Probe-B Ad Hoc Committee Report

Implementation: Gravity Probe-B (GP-B)

- **A cardinal experiment, investigating a fundamental force of nature**
  - Precision test of the frame-dragging effect, where Einstein's theory may be the weakest
  - Additional test of geodetic precession – will be the most accurate test yet accomplished of general relativity, a two orders-of-magnitude improvement
  - Potential to revolutionize our understanding of the Universe, from large-scale structure to the link between atomic forces and gravity
- **Not a traditional space science mission**
- **Many technical advances have already been produced to make this program possible, for example**
  - Liquid Helium porous plug, crucial to IRAS, COBE and SIRTF missions
  - Drag-free satellite control, now standard on Navy Transit navigation satellites
- **Effective training tool for scientists, engineers and managers**
  - Innovative Stanford University management highly successful
  - 33 Ph.D. degrees awarded for student research on this program
  - 40 graduate students and 10 undergraduates from 8 universities currently working on this program

Strategy for the Future

Astrophysics Strategic Plan

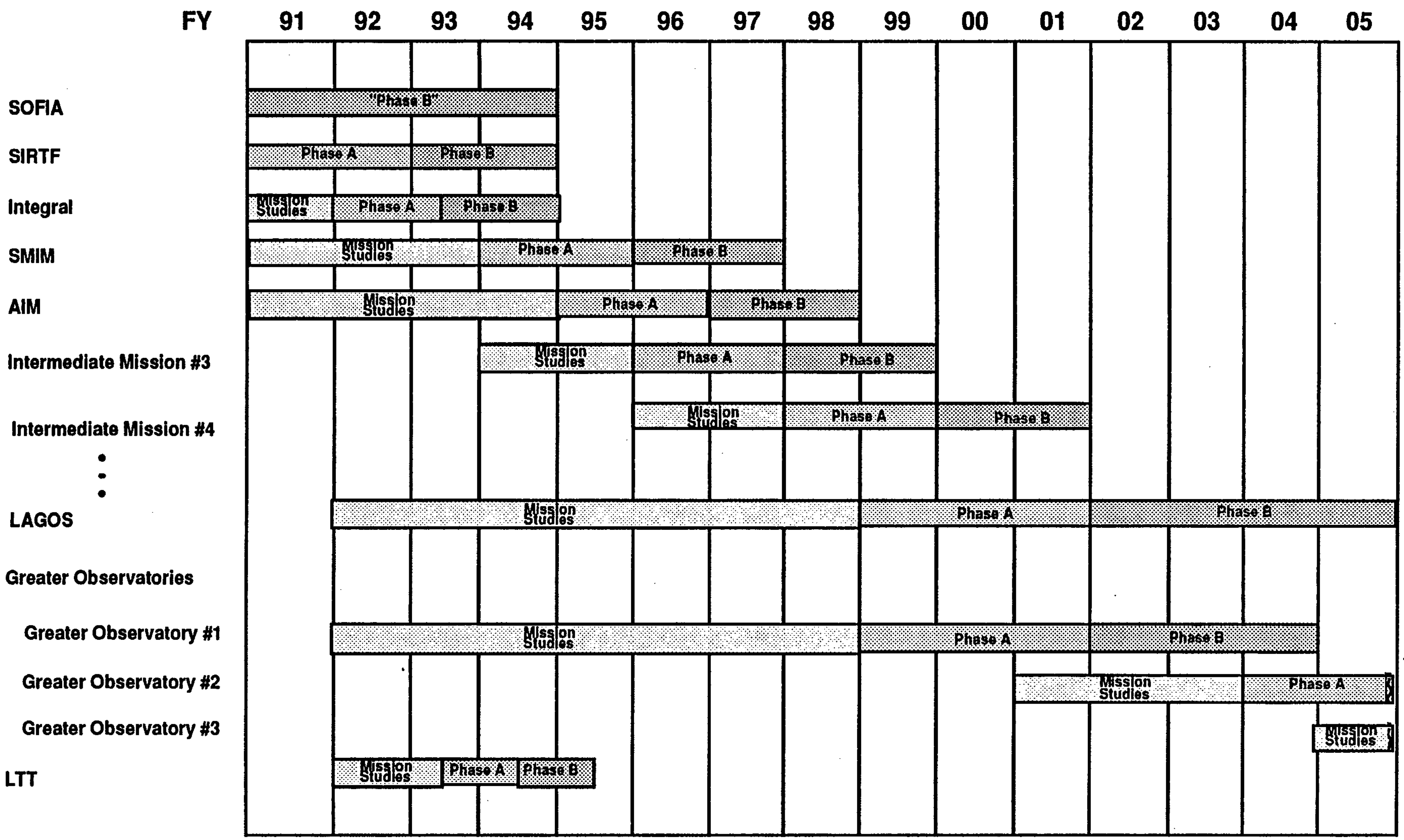
	Flagship Missions	Intermediate Profile Missions	Small Missions	Research and Technology Enhancements	Mission From Planet Earth
1994			Explorer Augmentation		
1995	SIRTF			SOFIA*	
1996					
1997			Integral**		Lunar Transit Telescope
1998		Sub-millimeter Intermediate Mission			
1999	Astrometric Interferometry Mission	NAE**			
2000	Greater Observatories e.g., Next Generation Space Telescope Very High Throughput Facility Large Deployable Reflector	Intermediate Mission Three***			
2004		Intermediate Mission Four***			Lunar Interferometer

* = Un-queued in OSSA Strategic Plan

** = Joint ESA/NASA Integral Mission or US-only Nuclear Astrophysics Experiment

*** = Selection of missions based on peer review from Announcement of Opportunity

Astrophysics Future Mission Pre-Development Schedule



Relationship Between Astrophysics Missions and Technology Development

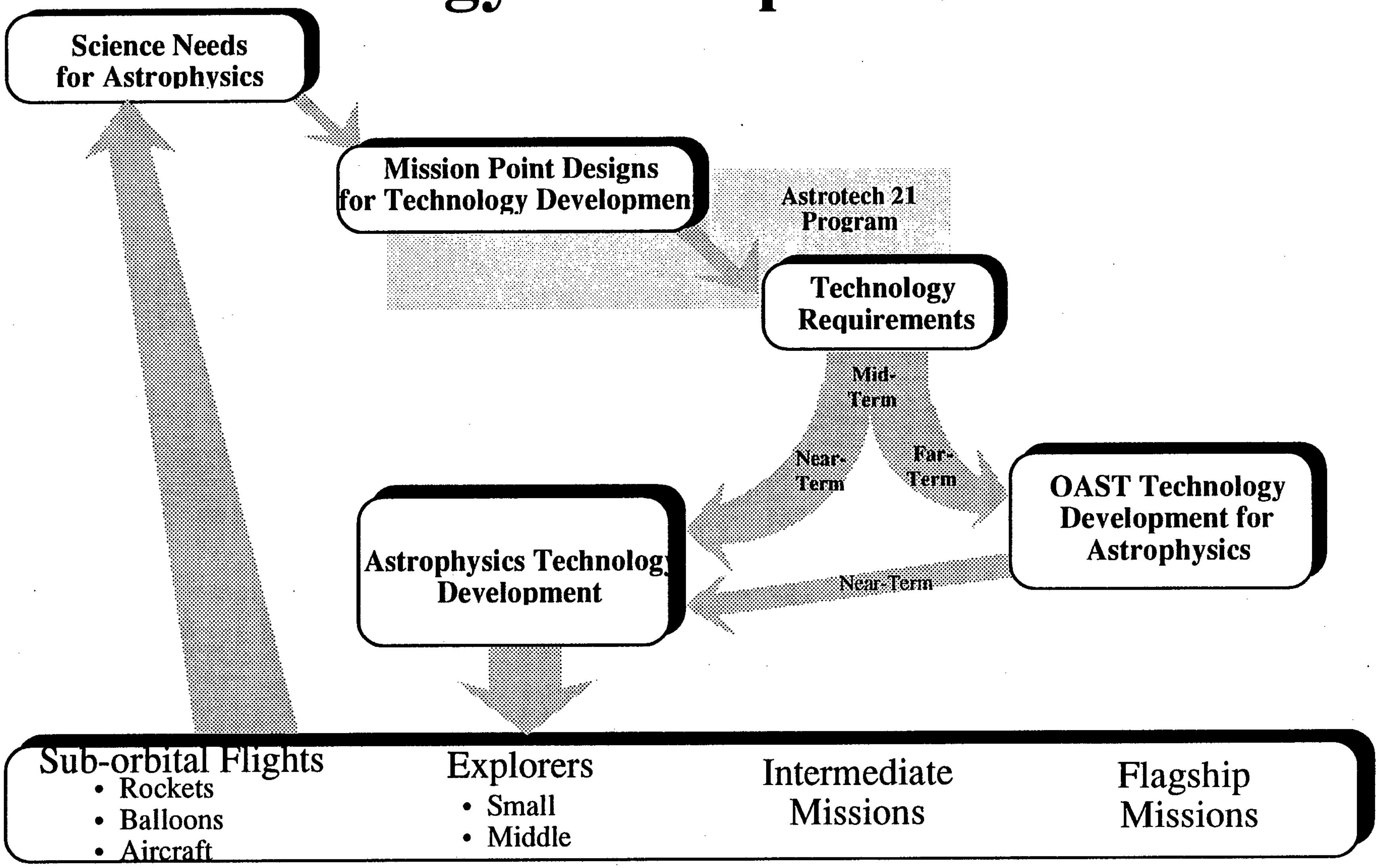
- Technology development will play an major role in future astrophysics missions
  - Enable new techniques to understand our universe
  - Enhance current capabilities of obtaining observations
- Technology development must be timely
  - Goal is to have technology development complete by Non-Advocate Review (NAR) – NASA milestone approximately 18 months before development commences
  - Very inefficient to develop technology during development phase
- Critical to
  - Define future technology needs
  - Initiate technology development programs to meet these needs in a timely manner

Technology Development Planning Process

Astrotech 21 Program

- Define science goals and objectives
- Develop "point design" mission concepts
- Identify technology development needs
- Develop technology development plans to meet those needs
- Develop technology development priorities
- Develop technology development plans
  - For each future mission
  - For each discipline

Technology Development Process

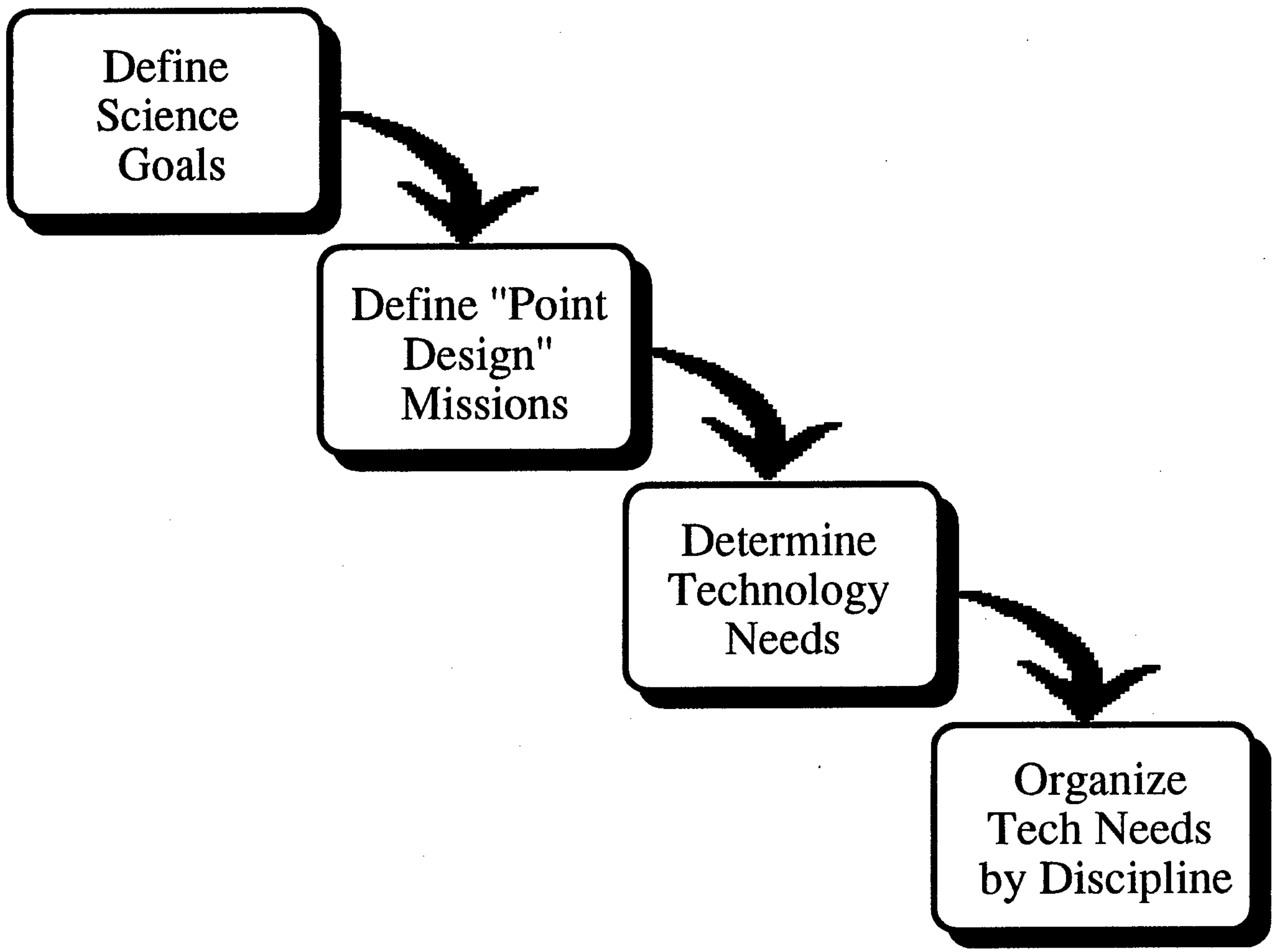


Astrotech 21 Program

- Program Goals:
  - To determine technology development needs for future astrophysics missions
  - To define technology development plans to address those needs
- Initiated in 1989 to technology needs for future Astrophysics missions
  - Over $2M dollars spent on the program to date
- Managed by JPL
  - Active participation of hundreds of scientists and engineers
  - Involved most NASA field centers, universities, other Government laboratories and private industry

Astrotech 21 Program (cont'd)

Conducted a series of workshops to define needs



Astrotech 21 Planning Results

- Three of four integrated technology planning workshops have had results published
  - Information Systems Technology
  - Sensors Technology
  - Optics Technology
- Fourth workshop will be held in the beginning of FY 93 in the area of Observatory Systems technology
- **Resulted in a regular, ongoing dialog between the Astrophysics Division and OAST**

Setting Priorities for Technology Development

- Priorities based on several criteria, in order of importance:
  - *Urgency*: When is the technology needed?
  - *Criticality*: Is the technology enabling or enhancing to the mission?
  - *Difficulty*: How much effort is required compared to the state of the art?
- Criteria applied to results of Astrotech 21 program to develop a prioritized list of technology development needs
  - Results endorsed by scientific discipline advisory groups and science working group

Astrophysics Technology Development Needs

Near-Term Needs

Mission (Tech Readiness Date)	Highest Priority	Higher Priority	High Priority
SIRTF (94)	• Low noise, low temperature multiplexer • Low noise, low power cryogenic electronics • Cryogenic optics technology	• Large format Si:Sb IBC detector array • Ge:Ga IBC detector • Flight qualifiable Ge:Ga and Ge:Ga stressed photoconductor arrays	• On-board data compression & image processing • Observation planning & mission sequencing tools • Tools for adaptive sequencing of observations • Expert system for system health monitoring & fault isolation
SMIM (96)	• 1.2 Terrahertz SIS heterodyne receivers (LO, mixer & space-qualifiable receiver)	• 2.5 m, 100K lightweight aperture • Low power, small size, large bandwidth spectrometer	• Low vibration, long-life cryogenic cooler for 4 and 15 K at the focal plane
Integral/NAE (94/97)	• Segmented detector development • Pulse shape discrimination development • Enriched or isotopically pure Ge detectors	• Microphonics technology • Advanced FET development • Spectromter configuration studies	• Isotopically pure Be for detector housing • Radiation damage studies • Shielded cryogenics to 80K • Mechanical coolers and isolation
HST Adv. Insts. (96/99)	Large format CCDs (4k x 4k or larger) High UV QE CCDs (350 - 120 nm) • Solar blind, low noise CCDs • MCP-based devices	• High spatial resolution, radiation hard, high dynamic range detectors • Detector packaging & mosaicing technology	• High transmission UV filters • Non-Si CCDs, high bandgap sensors • Cosmic ray discrimination
AXAF Adv. Insts. (96)	• Large format cryogenic imaging / spectroscopy detectors • Large format advanced efficiency X-ray CCDs • X-ray grating technology (variable line spacing, conical gratings, large area, high line density, etc.)	• Superconducting tunnel junction detectors • Radiation hardening technology for CCDs	• On-board data compression and image processing • Advanced focal plane polarimetry

SIRTF = Space Infrared Telescope Facility, SMIM = Submillimeter Intermediate Mission, **Integral** = International Gamma Ray Laboratory, NAE = Nuclear Astrophysics Experiment, HST / ARC = Hubble SpaceTelescope, AXAF = Advanced X-Ray Astrophysics Facility

[shaded box] = Ongoing approved program

Mid- and Far-Term Needs

Mission	Highest Priority	Higher Priority	High Priority
Optical Interferometers AIM, II, XRI (98-10)	• Active delay lines • Stabilized lasers • Picometer laser metrology • Active control of optical paths at the 20 pm level • Phase stability detection	• Optical detectors • Thermal-control system • Lightweight, thermally stable optics • Low-drift gyros • Correlator • Thermally stable optical assemblies • Tunable lasers • Reactionless gimbal actuators • Spatial heterodyne x-ray detector optimized near 10 nm • X-ray fringe generation and detection	• 3-D packaging for 1 MByte solid-state memory chips • 15 - 20 MIPS processors • Very high precision optical surfaces • High accuracy star trackers • High efficiency solar cells & K-band transponders
IR/Submm/Radio OVLBI, LDR and IRST (00-15)	• 25 m deployable antenna - 30 microns RMS surface accuracy • Long lifetime cryogenic cooling to 30 K • 15 - 25 m, 100 K lightweight, segmented, passively-cooled, lightweight optics • Space qualifiable 3 Terahertz SIS heterodyne receivers	• Space qualified frequency standard - hydrogen maser and trapped ion clocks • Pointing technology for 3 arc sec for 25 m antenna • High sensitivity, photometrically accurate, radiation hard, low noise, IR detector arrays from 1 to 1000 microns	• Ultra-high bandwidth (gigabit per second) telemetry links for both Earth to space and space to space • Low vibration, long-life cryogenic coolers for focal plane instruments
UV/Visible LTT, ST, LLT (05-15)	• Active delay lines • Stabilized lasers • Nanometer laser metrology • Optical ray tracinmg simulation tools • Precise four-element optical alignment simulation tools and technology • Low CTE, lightweight optics at final operating temperature • Precision sensing and control	• Optical detectors • Thermal-control system • Lightweight, thermally stable optics • Low-drift gyros • Optical fabrication and testing to 3 nm rms • Correlator • Thermally stable optical assemblies • Tunable lasers • Reactionless gimbal actuators • Cryogenic optical end-to-end testing of complete systems	• Large format UV and visible detectors with greater pixel sensitivity, higher quantum efficiencies, radiation tolerance, low noise & high dynamic range • Low vibration, long life cryogenic coolers for 10 and 60 K• 3-D packaging for 1 MByte solid-state memory chips • 15 - 20 MIPS processors • High accuracy star trackers • High efficiency solar cells & K-band transponders
X-Ray/γ-Ray XST, HXIF, VHTF (00-15)	• Large, cooled Ge detectors • Large scintillation crystals • X-ray imaging systems • Coded apertures • Large area flat mirror technology • Multistep flourescence gated proportional counters • Mirror replication technology	• Liquid Xe or high pressure, low background position-sensitive detectors • Large area imaging detectors • X-ray grating technology (variable line spacing, conical gratings, large area, high line density, etc. • Grazing incidence mirror replication technology	• Bragg concentrators • Low-cost duplication of optics • High pressure gas scintillation chamber • Mirror substrate studies • Low cost pointing systems
Gravity Physics LAGOS (10)	• Drag-free or accelerometer technology -- proof-mass sensing and proof-mass charging control • Precision alignment, pointing & control of lasers	• Phase stabilized, space qualified lasers • Highly controllable, long lifetime, ultra-low thrust propulsional thrusters	• Lightweight materials with low CTE and low thermal conductivity to provide passive stability throughout the s/c

AIM = Astrometric Interferometry Mission, II = Imaging Interferometer, XRI = X-ray Interferometer, OVLBI = Orbiting VLBI, LDR - Large Deployable Reflecor, IRST = Infrared Space Telescope, LTT - Lunar Transit Telescope, ST = Space Telescope, LLT - Large Lunar Telescope, XST = X-ray Schmidt Telescope, HXIF = Hard X-ray Imaging Facility, VHTF = Very High Throughput Facility, LAGOS = Laser Gravitational Wave Observatory in Space

Technology Development Plans

- Division technology development strategic plan is nearly complete
- Components
  - •• Priorities
  - •• Needs description
    - By integrated technological discipline
    - By mission
      - -- SIRTF 3
      - -- SMIM 3
      - -- AIM
      - -- Explorer Program
  - •• Schedule with significant milestones
  - •• Required funding
    - Astrophysics Division responsibilities
    - OAST responsibilities

Technology Needs by Integrated Discipline

- Sensors Technology
- Optics Technology
- Interferometer Technology
- Observatory Systems Technology
- Information Systems Technology

Technology Driven by Astrophysics Missions

- The majority of astrophysics missions require technology that is either <u>unique</u> or <u>driven</u> by astrophysics requirements.
- Sensors technology is driven by astrophysics requirements, except for shorter wavelength infrared detectors (overlap with military missions) and visible-light detectors (e.g., CCD development largely accomplished for commercial applications)

  -- In general, astrophysics missions require more detectors of smaller size and greater sensitivity than other science areas (e.g., EOS) or the military

  -- Astrophysics requirements push the state-of-the-art for cryogenics and cryogenic electronics
- Most optical and interferometry technology are unique to astrophysics missions

  -- Size and precision of optical systems, scale of interferometry baselines, low-temperature operation driven by astrophysics requirements

  -- Little known commonality with military missions
- Observatory technology has significant commonality with spacecraft technology for other NASA, military, and commercial applications; however, precision pointing, thermal control, and frequency standard technologies are driven by astrophysics requirements
- Information systems technology for astrophysics is largely based upon commercial hardware

  -- On-board processors share commonality with analogous processors for the military and other NASA missions

  -- Software for simulation, modeling, and data analysis is often unique, but could have applicability to other science disciplines.

Sensors Technology Needs

- The fundamental enabling technology for major gains in both sensitivity and resolution for future astrophysics missions.
- Includes
  - Detectors,
  - Readout electronic
  - Cryo-coolers
- Many of Astrophysics' technology requirments are unique
  - High energy, extreme UV, far IR, and sub-millimeter detectors
  - Ultra low noise, low temperature multiplexers / readouts,
  - Long lifetime, low vibration cryo-coolers.
- Much of the required technology need breakthroughs, not just an evolution of the state-of-the-art.
  - In such cases, parallel activities are proposed until it is clear what the most promising technology might be.

Optics Technology Needs

- Major improvements, and in many cases breakthroughs, in Optics Technology will be required to enable future missions.
  - Require larger, lighter and more precise optical elements
  - Improvements in optical materials, fabrication, finishing and testing techniques, and modeling capability for both filled monolithic and segmented aperture telescopes are needed
- Encompasses more than just optical surfaces. It includes:
  - Mirror mounts
  - Support structures,
  - Metrology measurement and adjustment mechanisms and devices
  - Optics and their coatings.
- Building blocks for future space telescopes -- lightweight, stiff, durable and stable aspheric mirrors capable of operating at very low temperatures (~100 K)
- Precision Segmented Reflector (PSR) program is an excellent example of an OAST technology program that supports future astrophysics needs
- Cryogenic optical technology requires special attention to the problems of room temperature development and finishing of optics which are ultimately used at cryogenic temperatures in space.

Interferometer Technology Needs

- Based upon future mission concepts employing more than one aperture up to 30 meters in extent in space and hundreds of meters on the moon
- Includes
  - Metrology
  - Controls-Structures Interaction (CSI),
  - Active delay lines
  - Ultra-precision deployable structures,
  - Vibration isolation systems
- High precision metrology requirements within an element and between elements of an interferometer are a driving technology requirement
- CSI another example of an OAST program that directly supports future astrophysics missions,
- Precision control and deployment technology for large structures are major technology activities in this area that are common to both Optics and Observatory Systems technologies

Observatory Systems Technology Needs

- Includes
  - Pointing and control for future telescopes and instruments
  - Power sources
  - Frequency standards
  - Telemetry systems and components
  - Thermal control systems and component
  - System level performance and cost models
- Many technology requirements are generic to most future missions. This includes requirements for power sources and telemetry as well as much of the technology for pointing and thermal control.
- Missions involving large optics, including interferometers and gravity physics missions, will be drivers for the precision required for pointing, thermal control and time/frequency measurement technologies

Information Systems Technology Needs

- Primarily generic and much of what is needed is expected to evolve from the industrial base for commercial products.
- Improvements needed in
  - On-board processing,
  - Ground data processing and display
  - Operations/Mission Planning
- Software is often unique including software used for simulation, modeling and data processing
  - Software cross-fertilization between space science disciplines is limited and would be beneficial

Comments and Recommendations on Technology Development at NASA

- In the past there has not been a good working relationship between Astrophysics and OAST
  - Astrophysics conducted virtually all of its required technology development within its ATD program
  - Perception existed that OAST's program was isolated from user needs
- The situation is improving, but much change within OAST is still needed
  - Establishing priorities
  - Program planning
  - Program implementation

Establishing Priorities

Highest priority in OAST should be to support user needs

- Base program should be directed toward user technology needs
- Meeting user needs in the focused program cannot be relegated to merely seeking an augmentation to the ongoing program
- OAST can't conduct all of its research at the research centers
  - Significant fraction of astrophysics technology development conducted at universities and space flight centers
  - Most current OAST programs managed out of the research centers that have few, if any ties, with the astrophysics community
- Progress to date has been largely Headquarters-sponsored exercises which have generated lots of plans but little actual user-related funded effort and virtually no change in the base program

Program Planning

OAST & the Astrophysics Division should formulate joint technology development plans

- Needs originate within the Astrophysics Division
- OAST responsible for a significant portion of the early stages of technology development through focused programs
  - OAST programs should be paced to provide technologies according to user need dates
  - Every OAST focused program should have a technology transfer plan
  - OAST should take the lead for technology transfer
  - May involved ground or flight testing of critical aspects of the technology
  - Guarantees technology transfer
- Astrophysics ATD program funds application of technology to specific flight mission

Program Implementation

A peer-review process to select proposals should be used to the greatest extent possible

- Funding decisions have frequently been based on dividing up available funds evenly among OAST centers, not based on merit
- OAST should enable users to participate in technology development activities
  - Issue NRAs and AOs to solicit proposals as broadly as possible
    - Make minimal use of unsolicited proposals
  - A significant fraction of astrophysics technology is developed by the scientific community

Summary

- The future success of astrophysics is profoundly tied to the development of new technology
- The astrophysics community has defined and prioritied its technology needs
- OAST needs to continue down the path that has been underway for the past two years of becoming more "user-oriented" to increasing its support for astrophysics technology
- The needs are defined and prioritized, the advocacy is there -- ***Carpe diem***

Sensor Technology Needs for Astrophysics

Presentation to SSB/ASEB

June 24, 1992

Dr. Barbara Wilson/JPL

TECHNOLOGY/MISSION/REFERENCE MATRIX:

SENSORS

Briefing Topic	OSSA Chart Reference	Relevant Astrophysics (Code SZ) Missions	References
• Sub-millimeter Receivers	Submm & Microwave Tech: • SIS 1.2 THz Heterodyne Rec. SIS 3 THz Heterodyne Rec.	SMIM, IRST-NG, OVLBI-NG, SMMI	• AT 21 Workshop Procedings: Sensor Systems for Space Astrophysics in the 21st Century, August 1, 1991, Series III, Vol. 2, pp. 50-57
• Direct Infrared Detectors	Detectors: • IR Si & Ge Arrays	SIRTF, IRST-NG, ST-NG, AIM, SMIM, II	• Op. Cit., pp. 34-49
• Optical Detectors - UV/Visible	Detectors: • Optical • CCD	HST-STIS & ORI, ST-NG, FUSE, AIM	• Op. Cit., pp. 27-33
• High Energy Sensors	Detectors: • Xe • High Purity Ge • Tunnel • CCD	HXIF, VHTF, AXAF 2nd Gen Inst, NAE, XST, GRSO	• Op. Cit., pp. 18-26
• Readouts & Multiplexer Electronics	Detectors: • Multiplexers • Readout Electronics Cryogenic Systems: • Electronics FET Development	HST, SIRTF, IRST-NG, AIM, LTT, NAE, GRSO, FUSE, AXAF, XST, HXIF, VHTF	• Op. Cit., pp. 45-48, 58-67
• Sensor Cryocoolers	Cryogenic Systems: • Coolers Vibration Isolation Technology Microphonics Technology	SIRTF, SMIM, ST-NG, NAE, AXAF, OVLBI-NG, II, IRST-NG	• Op. Cit., pp. 68-76

Sensors Technology Needs

- The fundamental enabling technology for major gains in both sensitivity and resolution for future astrophysics missions.
- Includes:
  - Detectors,
  - Readout electronic
  - Cryocoolers
- Many astrophysics technology requirements are unique:
  - High energy, extreme UV, far IR, and sub-millimeter detectors
  - Ultra low noise, low temperature multiplexers / readouts,
  - Long lifetime, low vibration cryo-coolers.
- Much of the required technology need breakthroughs, not just an evolution of the state-of-the-art.
  - In such cases, parallel activities are proposed until it is clear what the most promising technology might be.

Submillimeter Receiver Technology

HIGHLIGHTS

- Submillimeter receivers still in early stages of development
- Critical for identifying constituents of planetary atmospheres and cold interstellar material
- Key elements include oscillators and mixers for THz response, arrays for imaging, and back-end spectrometers

Submillimeter Receiver Technology (Cont'd)

- **Objective:**
  - Develop robust, space-qualifiable heterodyne technology for extension into the terahertz regime, increased sensitivity and array applications
- **Applications / Mission Enabled:**
  - SMIM, IRST-NG, OVLBI-NG, SMMI

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. Local Oscillators	1 mW @ 205 GHz (UARS/MLS) 3mW @ 275 GHz (development) 100µW @ 630 GHz (lab)	50 µW @ 1.2 THz full freq. coverage 20 µW @ 2 THz 100 µW @ 3 THz	'96 '06 '06
2. Mixers (SIS & other technologies)	200 hv/k @ 205 GHz, room temp operation (UARS/MLS); 120 hv/k @ 557 GHz, 150 K operation (development) 6 hv/k @ 492 GHz, 2K operation (lab)	350-1200 GHz, T , 20 hv/k 100-3000 GHz, T < 10 hv/k (FPA)	'96 '06
3. Spectrometers			
- AOS Filter Spectrometer	1000 chs @ 1 MHz resolution	8000 chs @ 1 MHz resolution 20,000 chs @ 1 MHz resolution	'96 '06
- Digital Spectrometer	Concepts	20,000 chs @ 1 MHz resolution (monitor technology to '95)	'06
4. Focal Plane Arrays	Ground-based arrays @ < 250 GHz	2 x 10 arrays, 100-3000 GHz	'06

Submillimeter Receiver Technology (Cont'd)

- **Payoff / Performance**:
  - Terahertz capability opens up entirely new areas of spectroscopy in the sub-mm regime. The development of arrays provides significant imaging capability improvement.
- **Existing Efforts**:
  - On-going efforts in OSSA, OAST (under the CSTI), and SDIO (for communications applications).
- **Issues**:
  - None

Direct IR Detectors

HIGHLIGHTS

- Many of NASA's IR needs are unique
  - Far IR - new technologies required
  - Low signals - high sensitivity, photon counters
  - Decade-long missions - 30-65 K sensors, advanced cryocoolers
  - Broad field of view, high spatial resolution - large format arrays & readout

Direct IR Detectors (Cont'd)

- **Objective:**
  - Develop sensitive, photometrically accurate, radiation-hard, low-noise, infrared detector arrays with response from 1 - 1000 μm.
- **Applications / Missions Enabled:**
  - **SIRTF**, IRST-NG, ST-NG, **AIM**, **SMIM**, II

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. Large Format Arrays	128 x 128 Si:As, $\lambda \leq 30$ μm 3 x 32 Ge:Ga, 40 μm $\leq \lambda \leq$ 120 μm 5 x 5 stressed Ge:Ga, 120 μm $\leq \lambda \leq$ 200 μm 8 x 8 discrete Bolometer, $\lambda \geq 200$ μm	>1k x 1k, $\lambda \leq 30$ μm 128 x 128, 40 μm $\leq \lambda \leq$ 120 μm 128 x 128, 120 μm $\leq \lambda \leq$ 200 μm up to 128 x 128, $\lambda \geq 200$ μm	'00 '06 '06 '06
2. Photon Counting Detectors	Si:As SSPM, QE ~30%, single pixels, 8-28 μm	1-5 μm photon ctrs/readouts 5-30 μm, Si SSPM arrays 30-200 μm, Ge SSPM arrays	'00 '00 '00
3. High-Temp (30-80 K) 8-17 μm Detector Arrays	PV HgCdTe, QE ~80%, 40-60 K, 1-12 μm bandgap-engineered technologies (e.g., superlattices & quantum well devices) – leakage-current limited	B/G-limit Performance, 30-65 K, 8-17 μm, ~1k x 1k	'96
4. IBC (BIB) Detector Arrays	Si:Sb IBC - "bulk" detectors Ge:Ga IBC - discrete devises, bulk detectors	128 x 128 arrays, QE $\geq$ 30% 512 x 512 arrays, QE $\geq$ 30%	'95 '98

Direct IR Detectors (Cont'd)

- **Payoff / Performance**:
  - Large Format Arrays -- Improved spatial and spectral resolution; dramatically increased observing/mapping efficiency
  - Photon Counting Detectors -- Greater sensitivity
  - Higher Temp (30-65 K) 8-17 mm Detector Arrays -- Reduced demand for cryogenic system performance, and reduced expense
  - IBC (BIB) Detector Arrays -- Improved radiation susceptibility, greater linearity
- **Existing Efforts**:
  - On-going developments in OSSA and OAST, including SIRTF-specific technology; and DoD (2-30 mm only)
- **Issues**:
  - Possible classification issue on Si:xx IBC arrays with DoD (SDIO)

Optical Detectors - UV/Visible

HIGHLIGHTS

- Visible range most highly developed. Concern over future viability of industrial base for this mature technology.
- EUV least developed, most demanding. Primary challenge is sensitivity to UV in overwhelming visible/IR background.

Optical Detectors - UV/Visible (Cont'd)

- **Objective:**
  - Develop large-format ultraviolet and visible detectors with greater pixel density, higher quantum efficiency, radiation tolerance, low noise, and high dynamic range.
- **Applications / Missions Enabled:**
  - **HST- STIS & ORI, ST-NG, FUSE, AIM**

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. Solar-blind Photocathodes (0.01-0.3 μm)	QE ~30% @ 0.12 μm	QE > 50%, 0.01-0.15μm QE > 50%, 0.15-0.3 μm	'93 '02
2. Short Pass UV Filters	No existing technology	λmax > 0.25-0.3 μm; Trans > 50% @ 0.12 μm, $<10^{-4}$ @ 0.55 μm, diameter ~75 μm	'96
3. Advanced Microchannel Plates (MCP)	Low count rate, 10 μm channels, spatial uniformity 20-50 μm	Low noise, non-distorting, count rate > 1000 cts/ch-sec, 6 μm channels, diameter ~ 100 μm	'02
4. Cryogenic 3-D Detectors	No existing technology	Prototype, high spatial & energy res.	'02
5. Advanced Si CCDs (0.3-0.9 μm)	800 x 800 pixels, QE > 15% @ 0.1-1.0 μm; 10 e- rms read noise (HST - WF/PC 1); 4k x 4k pixels, QE ~30% @ 0.1-0.4 μm, >60% @ 0.4-1.0 μm, 0.4 e- rms read noise (lab)	15k x 15k pixels, QE > 80%, 0.1-1.0 μm, 0.1 e- rms read noise	'02
6. Monolithic Non-Si CCDs/CIDs (0.7-2.5 μm)	Concepts only	High bandgap prototype	'96
7. New Materials	Concepts only	Opaque negative-affinity photocathode prototypes	'98

Optical Detectors - UV/Visible (Cont'd)

- **Payoff / Performance:**
  - Improved resolution and sensitivity for UV/VIS observations, EUV signal discrimination in strong UV/IR background.
- **Existing Efforts:**
  - Among on-going developments are OSSA-sponsored efforts related to future HST instrumentation, particularly for STIS II. There is little or no effort going on in DoD or industry for CCDs or MCPs with performance capability required for future astrophysics space missions.
- **Issues:**
  - Few industrial sources for CCDs and MCPs -- funding necessary to attract and maintain industry interest in advanced devices for astrophysics. Without steady funding in this area, breakthroughs required to enable post-2000 missions such as ST-NG are unlikely.

High Energy Sensors

HIGHLIGHTS

- High energy sensors are one of the least developed technologies
- Entire new areas of study enabled through ability to
  - Identify individual sources (enhanced spatial resolution)
  - Probe energy spectrum (enhanced energy resolution)
- Lack of commercial drivers

High Energy Sensors (Cont'd)

- **Objective:**
  - Develop technologies that offer order-of-magnitude advance in energy range and throughput; in particular, high-sensitivity and large-format X-ray detectors to 10 keV, and high-sensitivity position-sensitive γ-ray detectors to 2 MeV
- **Applications / Missions Enabled:**
  - HXIF, VHTF, **AXAF 2nd Generation Instruments, NAE**, XST, GRSO

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. High Sensitivity, High Spatial & Spectral Resolution γ-ray Detectors & readouts (10 keV to 10 MeV)	QE = 30-40% @ 100-1000 MeV Spatial res. ~mm Energy res. E/ΔE ~10	Large volume, high sensitivity Spatial resolution < 1 mm Energy resolution E/ ΔE > 1000	'92 - '96
2. Cryogenic Detectors for range of a few eV to a few hundred keV	1 x 12 arrays; Energy res. = 7 eV @ 6 keV	Large format, 10 x 10 to 2000 x 2000 Energy resolution: ≤ 0.5 eV @ 100 eV; ≤ 5 eV @ 8 keV; ≤ 100 eV @ 100 keV	'95 - '03
3. Advanced X-ray CCDs for 100 eV to 10 keV with smart readouts	QE ~75%; Energy range 0.3-8 keV; Energy res. = 90 eV; Spatial res. = 60mm; radiation-induced degrad.	QE > 90%; Energy res. = 60 eV; Spatial res. = 15 to 50 mm; Detector size = 1 to 4 cm; radiation hard	'95 - '03
4. Gas & Liquid Volume Interaction Chambers for Position-Sensitive Detectors at 5 to 500 keV	Ground Based liquid chamber	Position res. = 200-500 μm; Energy res. E/ ΔE ~10 to 100	'95 - '03
5. Solid Volume Interaction Chambers for Large Position-Sensitive Detectors at 200 keV to MeV	Concept only	Area > a few sq. meters; high stopping power; 2D res. to 1-2 mm	'93 - '98

High Energy Sensors (Cont'd)

- **Payoff / Performance:**
  - High Sensitivity, High Spatial & Spectral Resolution γ-ray Detectors (10 keV to 10 MeV): Adding spatial resolution to Ge spectrometers will allow high-resolution spectroscopy with the position-finding capabilities of coded-aperture or Compton telescope schemes.
  - Cryogenic Detectors: Larger format arrays will provide greater spatial resolution and increased sensitivity; improved energy resolution increases efficacy of spectroscopic studies of high-energy sources
  - Extended-Range X-ray CCDs: potential for large arrays using an existing industrial base, offers important imaging capability
  - Gas & Liquid Position-Sensing Detectors: Higher res. will allow individual high-energy sources to be identified
  - Solid Scintillator: For photons in the 0.02 - 2 MeV range, only solid scintillators have the stopping power to detect and resolve sources such as AGN and other high-energy compact objects, like neutron stars or even black holes.
- **Existing Efforts:**
  - High Sensitivity, High Spatial & Spectral Resolution γ-ray Detectors (10 keV to 10 MeV): balloon Advanced Compton Telescope (ACT)
  - Cryogenic Detectors: Semiconductor calorimeters for the AXAF spectrometer
  - Extended-Range X-ray CCDs: AXAF
  - Gas & Liquid Position-Sensing Detectors: Lab. demo of improved multistep & fluorescence gating only; for the rest, concept only.
  - Solid Scintillator: Concept only
- **Issues:**
  - None.

Readout & Multiplexer Electronics

HIGHLIGHTS

- Critical, but often overlooked element of sensor system
- Many of NASA's needs are unique
  - Weak signals - low temperature, low noise
  - Large field of view, high resolution - large format
  - Specialized instrument requirements - new sensor architectures
- Coordination of transducer and readout development is imperative

Readout & Multiplexer Electronics (Cont'd)

- **Objective:**
  - Develop multiplexers/readout electronics that are consistent with operational requirements of astrophysics missions, including cryogenic-temperature operation devices, ultra-low noise devices, and devices for reading out large-format detector arrays.
- **Applications / Missions Enabled:**
  - All deep-space spectroscopy and mapping missions in the UV, Vis, IR, Sub-mm, X-ray and γ-ray regimes - **HST**, **SIRTF**, IRST-NG, **AIM,** LTT, NAE, GRSO, **FUSE**, **AXAF**, XST, HXIF, VHTF

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. Low Noise Cryo Readouts	Si MOS discrete FETs, 4 e- read noise, T > 20 K; Si MOS array FETs, 50 e- read noise, T < 20 K	1k x 1k Array Compatible, ≤ 1 e- read noise, 2 K < T < 4 K	'96 - '01
		1k x 1k Array Compatible, ≤ 1 e- read noise, 60 K < T < 80 K	'96 - '01
		128 x 128 Bolometer Array Compatible, ≤ 1 e- read noise, T < 0.1 K	'00
2. Advanced Focal Plane Interface	Concepts only	Cryo On-Focal-Plane A/D	'97
		Optical Fiber Link to Focal Plane	'98
3. Advanced Architectures (smart readouts)	Concepts only	Event-Driven (X-ray) Digital Imaging Pixel (all) MCP Readout (UV)	'98 - '10

Readout & Multiplexer Electronics (Cont'd)

- **Payoff / Performance**:
  - Improved performance at low temperature operation, single temperature IR focal plane arrays, lower noise, signal enhancement, higher speed and more capacity for reading out large arrays.
- **Existing Efforts**:
  - Cryo readout technology under development in OSSA and OAST, including SIRTF-specific technology. DoD (SDIO) MODIL program addressing superconducting readout electronics.
- **Issues**:
  - Historically, sensor development in both NASA and DoD has focused on the transducer (detector), with the readout relegated to the later stages of system development. For large, ultra-low noise arrays, readout development should, in the future, be closely tied to detector/sensor development.

Sensor Cryocooler Technology

HIGHLIGHTS

- New sensor technologies require concomitant cooler development
- Many applications are specific to NASA
  - Enhanced spatial resolution - "vibrationless" coolers
  - Decade-long missions - long-life systems
  - Weak signals - 2-5 K coolers
- Emerging technologies need to be explored in parallel

Sensor Cryocoolers (Cont'd)

- **Objective:**
  - Develop reliable, efficient, vibrationless, intermediate-temperature and sub-kelvin cryocoolers
- **Applications / Missions Enabled:**
  - **SIRTF, SMIM**, ST-NG, **NAE, AXAF**, OVLBI-NG, II, IRST-NG

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• 2-5 K Long Life Mechanical Refrigerators	No existing technology	10-20 mW @ 2 K, 5-100 mW @ 4-5 K, < 1 kW input power	'95 - '96
• Long Life, Vibrationless Coolers	Large, ground-based systems, lifetime not demonstrated	65 K sorption & Brayton 10-30 K sorption & Brayton	'95
• Flight Testing of Emerging Prototypes	Concepts only	65 K Stirling, subkelvin ADR, etc.	'02
• R&D of Backup Technologies	Concepts only	Lower parasitic heat loads, alternate subkelvin & vibration-free concepts	'98
• Microphonics Technology (NAE/Integral)	Stirling cooler's vibration spectrum measured; cooler noise is the limiting technol. for energy resol.	Computer & lab simulation of cooler noise generation; improved noise damping technol. + smoother refrig operation in order to achieve required 1-2 keV resolution	'94 - '97

Sensor Cryocoolers (Cont'd)

- **Payoff / Performance:**
  - Long-life precision pointing space telescope type missions in the near to mid IR require vibration-free coolers with ~ 1W @ 65-80 K for 2.5 μm detectors, and with ~ 20 mW @ 10 - 20 K for 10 μm detectors. The no-vibration requirement is expected to exclude present Stirling cooler technologies being developed for EOS. Stored cryogens will not be cost-effective for 10 - 15 year missions.
  - Similarly, long-life missions at 2-5 K requiring > 100 mW cooling capacity exceed by an order of magnitude the capability of cryogenic systems being developed presently for SIRTF, and are probably unrealistic for a stored cryogen system.
  - New alternative technologies must be identified and flight tested before being committed to high-visibility astrophysics missions that demand a very low risk of failure.
- **Existing Efforts:**
  - New sorption and turbo-Brayton approaches have been demonstrated at the lab-breadboard level. Currently prototype turbo-Brayton coolers have capacities of 2.5 W @ 8.5 K, 9 W @ 25 K, 80 W @ 70 K, requiring ~ 3 kW input power. Only the Oxford Stirling cooler (used on UARS) is even space-qualified (0.8 W @ liquid nitrogen temperatures). Proven engineering models exist for other Stirling and turbo-Brayton designs in the 10 - 80 K range, as well as mW-capacity ADR and He-3 cryostats.
- **Issues:**
  - None

Sensor Technologies Overall Priorities

HIGHEST: Terahertz and submillimeter receiver technologies

Long wavelength and IR arrays

Low-noise cryogenic readout electronics

HIGHER: Long-life, vibrationless cryocoolers

Photon-counting detectors for the IR

High-sensitivity and -resolution gamma- and X-ray detectors

HIGH: Advanced microchannel plates for far UV

X-ray CCDs

Gas, liquid, and volume interaction chambers for gamma-ray detection

Smart readouts and advanced focal-plane architectures

Optics Technology Needs for Astrophysics

Presentation to SSB/ASEB

June 24, 1992

Dr. Chris Burrows/STScI

TECHNOLOGY/MISSION/REFERENCE MATRIX:

OPTICS

Briefing Topic	OSSA Chart Reference	Relevant Astrophysics (Code SZ) Missions	References
• Cryogenic Optics Technology	Cryogenic Optical Verification, Fabrication, and Testing	SIRTF, etc.	• No specific references - These charts were derived from the soon-to-be-published Proceedings of the AT 21 Workshop on Optics
• 4-Meter, 100K, Lightweight Aspheric Mirrors	Large Filled Apertures • Lightweight & stable optics • 15-25m PSR 2.5-4m, 100K Lightweight PSR	IRST-NG, ST-NG, LTT	
• X-Ray Optics Technology	X-ray Optics Tech: • Imaging System • Low Cost Optics • Bragg Concentrators • Coded Apertures	XST, HXIF, VHTF	
• Optical Fabrication	Large Filled Apertures	Many	
• Optical Modeling	2.5-4m, 100K Lightweight PSR	SMIM	
• Optical Testing	Cryogenic Optical Verification, Fabrication, and Testing	Many	
• Materials, Structures, and Coatings: Reflectors	None	Many	
• Wavefront Sensing& Control	None	Many, esp. those involving multiple apertures, active optics, or segmented reflectors	

Optics Technology Needs

- Major improvements, and in many cases breakthroughs, in Optics Technology will be required to enable future missions.
  - Require larger, lighter and more precise optical elements
  - Improvements in optical materials, fabrication, finishing and testing techniques, and modeling capability for both filled monolithic and segmented aperture telescopes are needed
- Cryogenic optical technology requires special attention to the problems of room temperature development and finishing of optics which are ultimately used at cryogenic temperatures in space.
- Building blocks for future space telecopes -- lightweight, stiff, durable and stable aspheric mirrors capable of operating at very low temperatures (~100 K)
- Encompasses more than just optical surfaces. It includes:
  - Mirror mounts
  - Support structures,
  - Metrolgy measurement and adjustment mechanisms and devices
  - Optics and their coatings.
- Precision Segmented Reflector (PSR*) program is an excellent example of an OAST technology program that supports future astrophysics needs

* PSR program has been zeroed in FY93 budget.

Cryogenic Optics

HIGHLIGHTS

- Development of 0.7 to 1.0 meter primary mirror technology for operation at a few degrees Kelvin is of the highest priority to enable an FY96 SIRTF new start.

  --Fused Silica and Silicon Carbide are the primary candidate materials for the SIRTF primary.

  --Cryogenic mirror mount and telescope structure technology to be developed in conjunction with the development of cryogenic mirrors.

- Straylight rejection performance is critical for an earth orbiting infrared telescope.

  --Space qualified optical blacks operating to 200 μm wavelengths are critical to telescope straylight capability.

  --Contamination can severely degrade straylight performance--remedial and monitoring technologies, and better materials characterization, are required.

Cryogenic Optics (cont.)

Objectives:

- To extend the state-of-the art in mirrors, telescope support structures, and mirror mounts to enable telescopes with apertures as large as one meter that perform acceptably at temperatures in the few Kelvin range and which are flight qualifiable.

- To develop techniques for characterization, prevention and removal of contamination from cryogenic optical surfaces.

- To develop and demonstrate flight qualifiable black coatings and baffles for control of stray light in a cryogenic infrared telescope, including methods of analysis and verification.

Applications / Missions Enabled:

- SIRTF, SMIM, IRST-NG

Cryogenic Optics (cont.)

Required Technology	Current State of the Art	Science Mission Requirement	Readiness Date
0.7 to 1.0 meter diameter, lightweight cryogenic aspheric mirrors	6 μm diffraction limited performance at 4.2K, 0.5 meter diameter spherical mirror (fused quartz) -- for SIRTF	5 μm diffraction limited performance at 6K. Stable coefficent of thermal expansion. Low areal mass density and high stiffness to mass density. Either can be cryo-null figured or (preferrably) does not require cry-null figuring. Compatiable flight qualifiable mirror mounting technology.	'96
Telescope Structures	All beryllium structure (IRAS)	Match to mirror material. Suitable for passive thermalization Lightweight, hight stiffness to mass density.	'96
Cryo Optical Materials Fracture Mechanics	N/A	Determine the effects of subsurface damage on the optical performance of cyogenic optical components.	'96
Contamination Control	IRAS and COBE acheived acceptable levels of contamination on-orbit. Jetspray/laser mirror cleaners and cryo particulate and volatile contamination monitors are in development for DoD.	Improved techniques for characterization, prevention, and removal of contamination from cryogenic optical surfaces.	'96
Validate candidate coating (Ames 24E or derivative thereof) for cryo-flight environment	Coupon qualification completed including some cryo testing (basis for selection of Ames 24E)	Extend technology to large surface areas. Demonstrate qualification for cryo-flight environment.	'94
Verification of Straylight Prediction	Predictions of straylight performance using in-plane-of incidence BRDF data.	Extend computer code to use hemispherical BRDF to verify straylight prediction through test article.	'95

Cryogenic Optics (cont.)

- **Payoff / Performance:**

  High angular and spectral resolution resulting in hight efficiency in a discovery mission.

  Lightweight materials reduce overall launch weight, allowing for better performance and/or less expensive launch vehicles.

  Straylight control essential in order to achieve background limited observing in the infrared wavelengths.

  Contamination control an important factor in straylight control.

- **Existing Efforts:**

  Under OSSA funding, NASA Ames has cryo tested both fused quartz and lightweighted fused quartz mirrors up to 0.5 meter diameter.

  Under OAST funding, silicon carbide coupons are being evaluated for fundamental material properites.

  Both IR and D and DoD programs have developed lightweight mirrors in fused quartz, beryllium, and silicon carbide, but not for 2K operation.

  DoD has been developing mirror cleaning and monitoring technology for the Space Defense Initiative.

- **Issues:**

  Funding limited for development of 0.7 to 1.0 primary for SIRTF--may impact technology readiness for presently planned FY96 new start.

  Straylight predictions have always been optimistic compared to actual flight performance.

  Mechanical adherence of coatings to surface during vibration testing has been a problem (SIRTF).

4-meter, 100 K, Lightweight Aspheric Mirrors

HIGHLIGHTS

Lightweight, cryogenic 4-meter mirrors are the foundation for next-generation astronomical telescopes. Precision Segmented Reflector (PSR) technology improves the resolution and sensitivity of these telescopes, while reducing their complexity and cost. However, the PSR program has been zeroed in the FY93 budget.

Important areas of technological development for the production of these mirrors are the following:

- Cryogenic Testing
- Lightweight Blanks
- Mirror Finishing

4-meter, 100 K, Lightweight Aspheric Mirrors (cont.)

- **Objective:**
  - Develop the materials, structures, and control technology to enable the design and demonstration of lightweight 4-m aspheric reflectors with 2-3 nm rms surface figure capable of operating in the space environment at temperatures ≤ 100 K.

- **Applications / Missions Enabled:**
  - IRST-NG, ST-NG, LTT

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• 4-m Mirror Cryogenic Testing	2.5 m, CTE=0, 200 kg/m^2 @ 300 K (HST)	4 m, CTE=0, 60-80 kg/m^2 @ 80 K	'94
• 4-m Mirror Lightweight Blank	100 nm rms for 2.5-m mirror	2 - 3 nm rms	'96
• 4-m Mirror Finishing	1.5 m, 80 K, 10 nm (RADC)	4 m, 80 K, 2 nm	'96

4-meter, 100 K, Lightweight Aspheric Mirrors (cont.)

- **Payoff / Performance:**

  4-meter lightweight mirrors are the building blocks for the next generation astronomical telescopes. Without such technology, the resolution and sensitivity of these telescopes will be severely limited and the complexity (using smaller sized segments) and cost increased.

- **Existing Efforts:**

  OAST Precision Segmented Reflector (PSR) Program, part of the CSTI Program.

- **Issues:**

  PSR program has been zeroed in the FY93 budget.

X-ray Optics Technology

HIGHLIGHTS

- High-Throughput Imaging
  - -- Thin-Foil Optics
  - -- Bent-Glass Optics
  - -- Low-Cost Replication Optics
- High Angular Resolution Imaging
- High Resolution Reflective Imaging
- Wide-Field Imaging
- Multilayer Normal-Incidence Imaging
- Coded Apertures
- Bragg Concentrators

X-ray Optics Technology (cont.)

- **Objective**:
  - Develop enabling imaging systems and low-cost replication technologies necessary for X-ray astrophysics missions.

- **Applications / Missions Enabled**:
  - XST, HXIF, VHTF, other future X-ray missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• High-throughput Imaging			
- Thin-foil Optics	Mature	Sub-arc minute angular resolution	TBD
- Bent-glass Optics	Mature	Reduced mass, improved ang. res.	TBD
- Low-cost Replication Optics	Under development	Large-scale application of advanced ion-deposition techniques; novel uses of flat-plate reflective elements	TBD
• High Angular Resolution Imaging	< 1 arc sec resolution	Milli-arc sec. angular resolution	TBD
• High Resolution Reflective Imaging	10 keV	40 keV	TBD
• Wide-Field Imaging	Concept only	Better than 5 arcsec res. over 1° FOV	'94
• Multilayer Normal-Incidence Imaging	Small diameter	1-m diameter	TBD
• Coded Apertures	Lab prototypes	Up to 30 m^2	'04
• Bragg Concentrators	Lab prototypes	Monochromatic imaging from 20 keV to 2 MeV	'04

X-ray Optics Technology (cont.)

- **Payoff / Performance:**

  Throughput is usually increased at the expense of angular resolution and increased background noise. Resolution is improved at the expense of increased instrument length and mass. Current fabrication techniques are costly and slow. Improved replication technology will sharpen resolution while reducing weight and cost of future X-ray imaging telescopes. Coded apertures offer the high resolution of (multiple) pinhole cameras, which do not require reflecting or refracting elements, while overcoming the limited sensitivity of individual pinhole cameras. Bragg concentrators use multiple crystal diffractors to reflect and focus monochromatic radiation at energies too high for grazing-incidence systems.

- **Existing Efforts:**

  Large-area (~0.7 m^2) replicated X-ray optics, consisted of many nested shells, are being developed and tested for ESA's XMM mission. and the US/Italian Wide-Field X-ray Telescope (WFXT).

- **Issues:**

  Nested arrays of grazing-incidence telescopes are very dependent on adequate structural rigidity, which limits the packing of thin mirrors. To improve such arrays, innovative opto-structural design, testing and fabrication methods are needed.

Optical Fabrication

HIGHLIGHTS

- X-ray and Submillimeter Replicated Optics
  - -- Automated polishing of cylinders, with metrology feedback
  - -- Rapid production of cylinders
  - -- Double mandrel material
  - -- Precision composite facesheet replication and sandwich construction
- Large Optics Figuring
  - -- Figuring lightweight blanks 8 meters in diameter to 1 nm rms
- Innovative Technologies and Manufacturing Determinism
  - -- Reducing surface shape amplitudes at specific spatial frequencies
  - -- Reducing fabrication/metrology cycles
- Systems Issues in Optical Fabrication
  - -- Edge problems; adaptive thin meniscus mirrors; honeycomb design
  - -- On-orbit alignment and figure control
  - -- Smart structures to simplify optical fabrication and testing

Optical Fabrication:
X-ray and Sub-mm Replicated Optics

- **Objectives:**
  Develop enabling replication technologies necessary for X-ray and submillimeter astrophysics missions.

- **Applications / Missions Enabled:**
  VHTF, XST, SMIM, IRST-NG

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Automated polishing of cylinders, with metrology feedback	Zeiss Mandrells for XMM, 0.1 area needed & not as accurate	Single-cycle figuring of cylinders	'98
• Rapid production of cylinders	~1 yr for mirror with 1 as res., 1-3 Å finish	~50/yr	'99
• Double mandrel material	Aluminum substrates with nickel coatings, glass	Withstands >50 replications	'98
• Precision composite facesheet replication & sandwich construction	1-m aperture Gr/Ep, 1.2 mm rms (fig. & roughness); 0.5-m Gr/Ep, ≤ 3 mm rms on orbit	2-m aperture, 1-mm rms^2 thermal stability @ 80K areal densities ≤ 5 kg/m	'96-'03

Optical Fabrication

Large Optics Figuring

- **Objectives:**
  Figuring large optics to 1 nm rms

- **Applications / Missions Enabled:**
  LTT, FUSE, AIM, ST-NG, II, SOFIA

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
Lightweight Blank Fabrication Method Good for 1-nm Surface, 8-m Diameter	2.5 m @ 1 μm rms 8 m @ 3 μm rms	8 m @ 1 μm rms	'92 - '04
Surface Polishing	6 nm rms	Methods to convert generated to polished surface, 0.5-1 nm rms	'92 - '04
Precision, High-Resolution Metrology	10 nm, 256 pixels	Surf. contour meas. to 1 nm, mid spatial frequencies & high res. > 1000 pixels	'99
Deterministic Finishing	5-10 nm rms	Finish to 1 nm rms @ mid spatial freq; Accuracy > 5% of removal/step; Demonstrate rapid progression to final fig.	'94

Optical Fabrication

Innovative Technologies and Manufacturing Determinism

- **Objective:**

  Develop innovative techniques for fabricating advanced optical systems. Improve manufacturing determinism. Reduce surface shape amplitudes at specific spatial frequencies, reduce fab/metrology cycles, and maintain a continuous base level of funding necessary to advance the state-of-the-art.

- **Applications / Missions Enabled:**

  Many current and future missions, including large optics, broad frequency spectrum optics, AXAF production speed-up, FUSE

Required Technology	Current State of the Art	Mission Science Requirement	Date Needed
• Material Removal	Ion Milling -- Convergence: 0.1 - 0.05 Removal/Pass: 250 nm rms	Advanced techniques for monitoring/measuring material removal over large areas. Ion Milling: Convergence: 0.04-0.02; Removal/Pass: 10 nm rms with no subsurface damage; Ion Flux Stability: 1-2% spatially and temporally	'92-'02
• Adaptive Thin Film Systems	Being Assessed	Adv. techniques for continuously adaptive thin films	'92-'02
• High-Energy Optics	PACE, Ion Beam	Advanced Techniques: Replication of smooth foils for 40-100 keV regime; advanced PACE & ion beam. Area > 100 m2; res. < 0.1 as A 10 keV	'92-'02
• High-Energy Optical Designs	AXAF	Proof-of-concept fabrication: Kirkpatrick-Baez, foil, off-plane imaging, lobster-eye, HXR grazing-incidence	'92-'02
• Refractive Elements	Large-scale Refractive Elements not fully developed	Advanced techniques for developing complex refractive elements e.g., binary optics	'92-'02
• Processing Techniques	TBD	Advanced processing techniques to fab. & test aspherics: Bound & loose abrasive, mech/chem, post-polish figuring	'92-'02

Optical Fabrication:

Systems

- **Objective:**
  Systems issues in optical fabrication

- **Applications / Missions Enabled:**
  Enables Or Enhances Most Of The Mission Set

Required Technology	Current State of the Art	Mission Science Requirement	Date Needed
• Segment Fabrication	Keck (50 nm)	Investigate End-Effects vs. Segment Shape	'03
• Mounting	LOS (30 nm)	Develop Techniques for Fabricating & Mounting Adaptive Thin Miniscus Mirrors; Goal: < 30 nm	'03
• Rigidity	HST (2.5 m rigid, 10 nm)	Determine relationships among scale, rigidity, and control; understand spatial scale of transfer	'96
• On-orbit Techniques	HST	On-orbit Figure Initialization & Control	'96
• Smart Structures	NTT	Develop Smart Structures to Simplify Optical Fabrication & Testing	'96

Optical Fabrication (cont.)

- **Payoff / Performance:**

  The more that can be done to supply figure control actively, the less that needs to be done during the fabrication process, and the lighter the mirror substrate needs to be. Mirror systems are likely to have a combination of stiffness and flexibility requirements with varying spatial frequencies. The specification of these properties, and the translation of those specifications into practical materials and structural designs, is still in its infancy.

- **Existing Efforts:**

  Smart structure are currently being funded under NASA's CSI program at JPL.

- **Issues:**

  - The impact of wavefront control system flexibility requirements on the ability to achieve a smooth surface during the fabrication process
  - Edge effects produced because of new blank shapes, such as hexagonal or radial segments
  - Since mirror fabrication and system design tend to proceed in parallel, future designs must actively consider the mounting requirements during fabrication as equal to those for final use.

Optical Modeling

HIGHLIGHTS

- **End-to-end simulation capability**
  - -- Integrate optical, structural, control, and environmental design and analysis
- **Mission-specific design and analysis S/W**
- **Validation of integrated S/W and tools in the laboratory**
- **Research into basic techniques for optical system modeling**
  - -- Scattered-light evaluation
  - -- Scalar and vector diffraction
  - -- Image processing and inversion
  - -- Test data integration
  - -- Cryogenic heat transfer analysis
  - -- Modeling micro-mechanics of structural features

Optical Modeling (cont.)

- **Objectives:**
  - Develop & maintain end-to-end simulation capability for integrating optical, structural, control & environmental design & analysis, covering both preliminary design and detailed analysis.
  - Develop mission-specific design and analysis software.
  - Validate integrated software and tools using specific laboratory experiments.
  - Research into basic techniques for optical system modeling

- **Applications / Missions Enabled:**
  - All Mission; design & analysis S/W required especially for SMIM, AIM, ST-NG

Required Technology	Science Mission Requirement	Current State of the Art	Date Needed (prelim.-update)
• End-to-end Simulation	Front-end cross-discipline initial design S/W	None	
	Develop coupling S/W	Limited	'97 - '01
	Establish interface standards for existing S/W	Limited	'98 - '02
	Validate prog. modules against empirical data	Incomplete	'95 - '97
	Image chain anal., wavefront sens., active optics	Limited	'98 - '02
			'98 - '02
• Design & Analysis S/W	Analyze mission needs, devel.op package interconnections	Very limited	'97 - '02
	End-to-end demo on example space system	Nonexistent	'00 - '04

Optical Modeling (cont.)

Required Technology	Science Mission Requirement	Current State of the Art	Date Needed (prelim.-update)
• Validation	Validate simulation S/W against CSI or equivalent experimental H/W	Very limited	'98 - '03
	Validate propagation S/W against experimental demos	Theory only	'00 - '04
	Estab. & maintain materials & component database (esp. in micro properties)	Inadequate	'98 - '02
	Validate S/W pkgs against ground-based telescope obs. to support space predictions	Limited	'97 - '00
• Modeling Research	Scattered-light evaluation	Sparse database	'95 - '98
	Scalar &vector diffraction	E/M Polarization not used	'96 - '00
	Image processing & inversion	Limited experience	'96 - '00
	Test data integration	Non-correlated techniques	'97 - '01
	Cryogenic heat transfer analysis	Very limited	'97 - '00
	Modeling micro-mechanics of structural features	Limited	'99 - '04

Optical Modeling (cont.)

- **Payoff / Performance:**

  Future missions will be dominated by the size and complexity of the optics. Costly design and fabrication errors may be avoided if complex optical hardware designs are first tested using end-to-end modeling techniques that can simulate the overall functioning of interacting component subsystems.

- **Existing Efforts:**

  S/W packages (e.g., NASTRAN, ANSYS, SINDA, TRASYS, CODE V, GLAD, COMP, MATLAB, MATRIXX, EASY V, LINPACK, etc.) have been developed within several discrete technical disciplines for the separate analysis of the optical, structural, material, thermal, dynamic, science data and control aspects of telescopes, spacecraft, and missions. The Air Force initiated development of end-to-end simulation Integrated System Modeling (ISM) S/W, but has since cancelled its support.

- **Issues:**

  Existing S/W is available to carry out major portions of the modeling task, but it is generally in the form of dedicated packages for limited purposes. User-friendly visualization and animation S/W, particularly for small workstations and personal computers, needs to be developed.

Optical Testing

HIGHLIGHTS

- Surface figure parameters
  - -- rms, p-v, absolute ROC of large-aperture aspheric surfaces with high spatial resolution and speed (ground based).
- Surface roughness parameters
  - -- rms, p-v and power spectrum at spatial scales smaller than surface figure (mid-IR and shorter λ)
- Assembly and alignment of optical systems
  - -- Ground-based, lunar-surface, deployable
- Overall system performance
  - -- Monitoring image quality (encircled energy, etc.)
- Radiometric quantities
  - --Transmission reflectivity, absorption, radiance, irradiance, vignetting, polarization
- Stray light measurements, predictions and monitoring

Optical Testing (cont.)

- **Objectives:**
  1. Measure surface figure parameters, including rms, p-v, absolute ROC of large-aperture aspheric surfaces with high spatial res. and speed (ground based).
  2. Measure surface roughness parameters including rms, p-v and power spectrum at spatial scales not met by surface figure (mid-IR and shorter wavelengths)
  3. Assembly and alignment of optical systems -- ground-based, lunar-surface and deployable.
  4. Measure overall system performance by monitoring image quality (encircled energy, etc.)
  5. Measure radiometric quantities such as Transmission Reflectivity, Absorption, Radiance, Irradiance, Vignetting, and Polarization
  6. Stray light measurements, predictions and monitoring to meet mission requirements.

Applications / Missions Enabled:	**Freeze Date:**
1. AIM, ST-NG, II, IRST-NG, SMMI, SIRTF, AXAF, XST, HXIF	'92 - '04
2. ST-NG, AIM, II	'97 - '04
3. AIM, ST-NG, II, IRST-NG, SMMI, AXAF, XST	'92 - '04
4. AIM, ST-NG, II, IRST-NG, SMMI, SIRTF, AXAF, XST, HXIF	'92 - '04
5. AIM, ST-NG, II, SIRTF, XST, HXIF	'92 - '04
6. ALL MISSIONS	'95

Optical Testing (cont.)

Technology Area	Required Technology	Current State of the Art	Science Mission Requirement
1. Surface Figure	• Aspheric Measurements	HST, Keck	1 nm on f/1 surface
	• Large Convex Secondaries	Keck	1 m aperture
	• Gravitational Compensation	TBD	TBD
	• Cryogenic Measurements	SIRTF: 0.5m @10K	Meas. @ LN_2,LHe: 0.7-1 m @ 2K
	• Sources & Detectors	Visible +Near IR	TBD
	• X-ray Mirror Test	~200 Å over ~1 m pathlength (AXAF)	TBD
2. Surface Roughness	• Stitching S/W	WYKO (e.g.) for AXAF	S/W integration fig. & roughness testing
	• Sub-surface Damage Meas.	Limited, destructive techniques	Nondestructive techniques
	• Sampling Statistics	Cumbersome	Statistics on large surfaces
3. Assembly & Alignment	• System Assembly Tech.	Initial evaluation?	Align tech for partially assembled systems
	• Figure Initialization	Co-operative point sources	Init. & phasing of seg. optics in all DOF
	• Star Simulators	DoD	TBD
	• Alignment S/W	Few disciplines, limited data	Marriage of optical & mechanical S/W including gravitation, mounts & thermal
	• Laser guages	Good; need improvement?	Accuracy ≤ 1 nm
4. Image Quality	• Modeling	Limited	Adv. diffraction analysis & modeling S/W
	• Sources & Detectors	Vis ible and Near IR	TBD
	• System Wavefront Measurements	HST, Keck	Full aperture system wavefront (stitched)
5. Radiometric Quantities	• Reflectivity Measurement	Vis ible and Near IR only	Complex *n*, UV and X ray
	• Metrology	10%	Polarization metrology, full & partial systems analysis; 1%
	• Database	Limited	Polarization database
	• Calibration	10% absolute accuracy	Absolute radiometric calibration technique

Optical Testing (cont.)

Technology Area	Required Technology	Current State of the Art	Science Mission Requirement
6. Stray Light	• Stray Light Control	Nonexistent	Onboard system
	• BRDF	Limited	$\lambda < 0.4$ m; $2 < \lambda < 6$ nm; $\lambda > 20$ nm
	• Stray Light Testing	Broadband facility for apertures up to 3 m diam (AXAF)	Sy stem-level testing for all wavelengths, larger apertures
	• Signatures	Lacking H/W	H/W for Scatter/Muller polarization signatures
	• Sources & Detectors	Visible and Near IR	TBD
	• Scatter Measurements	Unknown	Near-angle @ TBD resolution
	• Calibration	Limited	TBD

Optical Testing (cont.)

- **Payoff / Performance:**

  Optical testing provides an opportunity to identify and rectify technical problems while still on the ground. It is necessary to create tractable test procedures that provide a true measure of the performance of all optical elements and systems under conditions simulating those in space. When testing is not feasible, accurate experiments are necessary for building models that predict optical performance. Where essential parameters are still unknown, they must be determined before practical models can be constructed.

- **Existing Efforts:**

  Cryogenic material data, high vacuum, and cryogenic test equipment facilities for testing optical systems in the X-ray regime has been built at NASA/Marshall Space Flight Center (MSFC). A cryogenic optical test facility for testing spherical mirrors up to 0.7 meters in diameter at liquid helium temperatures has been developed at NASA/Ames Research Center (ARC).

- **Issues:**

  - Difficult to find independent metrology to verify accuracy of surface figure testing at MSFC facility.
  - A cryogenic/high vacuum test facility with capability to test aspheric mirrors of up to 1-m diameter is needed to support IR missions as well, but the present level of funding for SIRTF technology does not allow for the development of such a facility in this vital wavelength regime.

Structures, Materials, and Coatings: Reflectors

HIGHLIGHTS

- Materials and Processing for PrecisionMirror Replication
- Materials and Designs for Optically Stable Mirrors (temporal , thermal)
- Large Area Segments and Monolithic Mirrors
- Materials and Techniques for Efficient High-Precision Figuring/Polishing
- Lightweight Materials for Large Mirrors
- Coatings:

-- Microstructure Engineering

-- Large-Area Processes

-- Advanced deposition technologies

-- New, High Performance Materials

-- Improved characterization technologies and analytical tools

Structures, Materials, and Coatings: Reflectors (cont.)

Objectives:

- Provide reflectors with required low areal density, high surface accuracy and smoothness, size, shape and optical stability at desired wavelengths and operating temperatures to support astrophysics missions

- Develop the technology for fabrication of reliable (durable, thermally and mechanically stable, chemically resistant) coatings on the scale required for astrophysics missions

Applications / Missions Enabled:

- Reflectors (by wavelength):
  - (1) X-ray: XST, VHTF
  - (2) UV/Visible: LTT, II, ST- NG
  - (3) IR: SIRTF, ST- NG
  - (4) FIR/Submm: SIRTF, IRST-NG, OVLBI, Submm and Lunar Interferometers
- Coatings:
  - (5) ST- NG, LAGOS, SIRTF, IRST-NG, AXAF

Structures, Materials, and Coatings: Reflectors (cont.)

Required Technology	Current State of the Art	Science Mission Requirement	Readiness Date
Materials and Processing for PrecisionMirror Replication	Epoxy, Graphite/epoxy, Electroforming, CVD	< 5 Å rms μ-Roughness, (1) < 2 as Slope Error (x-ray), (2) ≤ l/500 rms, visible	'00, '02
Materials and Designs for Optically Stable Mirrors (temporal , thermal)	70% Encircled Energy (Visible) in 0.1 as	Material/Design achieving ≥ 70% encircled energy (visible) in 0.025 as @ temperature used	'00
Large Area (1) Segments and (2) Monolithic Mirrors	0.1-2.5 m, depending on material	(1) ≥ 2 -m lightweight "identical" segments, (2) 6-8 m monolith	(1) '99 (2) '05
Materials and Techniques for Efficient High-Precision Figuring/Polishing	Glass, simple figures, many iterations	Material/Techniques achieving high-quality figure (mid-low spatial frequencies) and low μ-roughness on large areas in a small number of iterations	'98
Lightweight Materials for Large Mirrors	5-10 kg/m^2 – Graphite/epoxy, SiC 20-200 kg/m^2 - Glass 10-20 kg/m^2 - Be	(1) ≤ 2 m, 1-5 kg/m^2 (2) > 2 m, < 20 kg/m^2	'99, '02
(5) Coatings:			
• Microstructure Engineering	Rudimentary	Consistent, customized thin-film microstructures	'05, '10
• Large-Area Processes	~ 1 m	Coat 10-m reflective primary mirror	'99, '05
• Advanced Deposition Technologies, New, High Performance Materials	Application-specific techniques; traditional compounds, metals	High optical performance, low-scatter, durable coatings over a wide spectral range - Resistance to atomic oxygen	'95-'10 '02
• Improved Characterization Technologies & Analytical Tools	Material-specific	Measure thin-film properties @ all Temps. (esp. low); perform in situ Raman and X-ray spectroscopy	'98

Structures, Materials, and Coatings: Reflectors (cont.)

- **Payoff / Performance:**

  Technology for reproducible, lightweight, optical-quality substrates essentially does not exist. Requirements for optical and X-ray coatings for astrophysics missions exceed the current state of the art. Existing technology is rudimentary, small-scale, and application- and material-specific. Improved reflector substrates and coating techniques will advance instrument precision, stability and durability, as well as allowing more generic manufacturing techniques to be developed.

- **Existing Efforts:**

  NASA PSR effort has developed a 0.5-meter spherical mirror operating at 200 K with surface roughness better than 3 microns, which is the current state-of -the-art capability. Independent R&D and DoD programs have sponsored 1-meter mirror developments in fused silica, beryllium, and silicon carbide. Current work is not capable of meeting the requirement.

- **Issues:**

  Current reflector development has been a joint effort by NASA and industry. It is desirable to go even farther in this direction, broadening the industrial and academic involvement in mirror development. The PSR program has been zeroed in FY93 budget.

Wavefront Sensing, Pointing, And Control

HIGHLIGHTS

- As the size of the optical system increases -- either to increase sensitivity or angular resolution -- traditional technologies for maintaining optical wavefront accuracy become prohibitively expensive or completely impractical. For space-based instruments, low-mass requirements and large temperature excursions further challenge existing technologies.
- Future developments in space-borne telescopes will be based in part on developments in ground-based systems, including active optics, such as a segmented design based on the Keck instrument at Mauna Kea.
- Another active optics approach uses a thin meniscus mirror with actuators, which has been demonstrated on the European Southern Observatory's New Technology Telescope (NTT), and is planned for use on the Very Large Telescope (VLT, comprised of four 8-m apertures).

Wavefront Sensing,Pointing & Control
System Control Architecture

- **Objective:**
  - Integration of component technologies (optics and structures) for optical system control
- **Applications / Missions Enabled:**
  - All Missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Theory and Algorithms	Disconnected	Systematic design & analysis theory for multi-loop optics control systems	'96-'10
• Controls-Systems Interaction (CSI)	Nonexistent	Optics control system loop decoupling techniques	'96
• Computation And Processing	Multiple independent serial digital processors	Massively parallel architectures & algorithms; Neural network prototype controllers	'97-'10
• Modeling and Simulation	Special-purpose Prototype, idealized	Simulation, design and analysis tool for control elements	'96-'04
• Optimal Design	Nonexistent	Multi-loop optics control system design optimization technique	'97-'10

Wavefront Sensing,Pointing & Control

Structures Control

- **Objective:**
  - Control vibration and changes in lightweight flexible structures to a level consistent with the performance envelope of optical control and pointing control subsystems

- **Applications / Missions Enabled:**
  - Large Aperture (> 4 m) Missions, Interferometers

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
Vibration Isolation Systems	Special purpose prototypes & passive techniques Isolation: 80 dB, 1-1000 Hz	Order-of-magnitude improvement, low-temperature operations Isolation: 100 dB, 0.1 Hz to 10 kHz Active Techniques, Magnetic Suspension	'97-'04
Damping Augmentation	Room temperature operation, not space-qualified	Low Temperature Damping Treatment, Low Temperature Active Damper	'97-'04
CSI	Analytical Studies; demonstrated under idealized conditions	Testbed Demonstrations	'97-'04
Modal control	Theoretical results	Modal Control System Demonstration	'97-'04
Smart Structures	Breadboards	Structural Shape Control System Demonstration	'97-'04
Integrated Structure-Control Design Optimization	Analytical Studies	Practical Control-Structure Optimal Design Tool	'97-'04

Wavefront Sensing,Pointing & Control

Active Optics

- **Objective:**
  - To achieve and maintain diffraction limited performance in large optical and submillimeter systems using active optical techniques

- **Applications / Missions Enabled:**
  - Optical Missions ($\geq$ 4 m) and Submillimeter Missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Figure Sensing	Low-resolution pupil-plane techniques, Shearing Interferometers, Hartman Sensors	Measure Figure to ~0.02 Waves	'95-'06
• Phasing Sensing	Breadboard, Electronic Sensors: 10 nm	Optical & Electronic Sensors: <1 nm Space Qualifiable Prototype Phasing Mirror	'95-'06
• Deformable Mirrors	Operation @ IR wavelengths; Low-resolution, micron range	High Resolution, Long Stroke, Deformable Mirror Operation @ visible wavelengths	'95-'05
• Actuators	0-100 μm stroke, 10 nm precision, <1 Hz BW Non-cryogenic	0-10 mm stroke, 1nm precision, >10 Hz BW Cryogenic	'95-'10
• Delay Lines/Fringe Trackers	Breadboards	Space Qualifiable, Prototype Delay Line & Fringe Tracker	'97-'10
• Line-Of-Sight Stabilization	Small diameter steering mirrors	Space Qualifiable, Large-Diameter, Momentum-Compensated Steering Mirror	'96-'06

Wavefront Sensing, Pointing, And Control (cont.)

- **Payoff / Performance:**

  A majority of future NASA astrophysics missions, from orbiting interferometers to 16-m lunar telescopes, all need to bring light from a large entrance aperture to the focal plane in a way that preserves the spatial coherence properties of the starlight. Only by preserving the phase of the incoming wavefront can many scientific observations be made. Telescopes with rigid primary mirrors much larger than 5 m in diameter are impractical because of gravity loading. New technologies for wavefront sensing, pointing and control hold the key to improving observatory design.

- **Existing Efforts:**

  At present, ground-based efforts in active optics exist in several places: the Mark III interferometer on Mt. Wilson, the Keck telescope at Mauna Kea, and the VLT being planned by ESA. The STARLAB Wavefront Control Experiment, based on DoD-developed adaptive optics, is a 69 degree-of-freedom system designed for use in space that incorporates a shearing interferometer as a wavefront sensor.

- **Issues:**

  This promising technology is still quite new. Adaptive optics, developed by DoD, has only recently been declassified.

Optics Technologies Overall Priorities

HIGHEST: Cryogenic Optics
Optical Testing -- Cryogenic Measurements

HIGHER: Wavefront Sensing, Pointing and Control
Optical Fabrication
-- Large Optics Figuring
-- X-ray and Sub-mm Replicated Optics
X-ray Optics Technology
Optical Testing (Noncryogenic)
Optical Fabrication
-- Innovative Techniques
-- Systems

HIGH: Optical Modeling
4-Meter, 100 K, Lightweight Aspheric Mirrors

Interferometer Technology Needs for Astrophysics

Presentation to SSB/ASEB

June 24, 1992

Dr. Michael Shao/JPL Dr. Robert Reasenberg/SAO

TECHNOLOGY/MISSION/REFERENCE MATRIX:

INTERFEROMETER TECHNOLOGY

Briefing Topic	OSSA Chart Reference	Relevant Astrophysics (Code SZ) Missions	References
• Metrology	Interferometer-specific Tech: • Picometer Metrology Lasers: Long-life, Stable, & Tuneable	AIM, II	• AT21 Workshop Proceedings: *Technologies for Optical Interferometry in Space*, September 15, 1991, Series II, Vol. 1, pp. 111-125, pp. 245-253
• Fine Pointing with Isolation	Interferometer-specific Tech: • Control-Structures Interaction Vibration Isolation Technology	AIM (POINTS)	• Op. Cit., pp. 43-78, pp. 87-90
• Active Delay Lines	Interferometer-specific Tech: • Active Delay Lines	AIM (OSI),II	
• Quiet Structures, Precision Deployment	• Controlled Structures/Large Antenna Structure Arrays/Deployable Interferometer-specific Tech • Control-Structures Interaction	AIM, II, OVLBI-NG	• Op. Cit., pp. 79-86
• Materials and Structures for Stiff Optical Instruments	None	AIM (POINTS), II	
• Thermally Stable Optical Elements	Lighweight & stable optics	AIM, II	

Interferometer Technology Needs

- Based upon future mission concepts employing more than one aperture with baselines up to 30 m in extent in space and hundreds of meters on the moon
- Includes
  - Metrology
  - Controls-Structures Interaction (CSI)
  - Active delay lines
  - Ultra-precision deployable structures
  - Vibration isolation systems
- High precision metrology requirements within an element and between elements of an interferometer are a driving technology requirement
- CSI is another example of an OAST program that directly supports future astrophysics missions
- Precision control and deployment technology for large structures are major technology activities in this area that are common to both Optics and Observatory Systems technologies

Metrology

HIGHLIGHTS

- Stabilized Lasers (to 1 part per billion)
- Laser gauges (to picometer accuracy) and their Components

  -- Modulators

  -- Optical Fibers

  -- Beamsplitters

  -- Integrated Optics
- Tunable Lasers for Absolute Laser gauging

  -- 300 GHz tuning range, frequency markers accurate to 1 part per billion
- Endpoints -- optical components aligned to 1 micron
- Holographic Optical Elements (HOE) -- diffractive efficiency uniform to 1%

Metrology (Cont'd)

- **Objective:**
  - Measurement of distances to sub-nanometer accuracies. Range of distances is from 1 to 100 m.
- **Applications / Missions Enabled:**
  - AIM, II

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
Stabilized Lasers	• Suitable lasers working in lab • Stabilized HeNe lasers commercially avail. 2 orders more stable than req.	1 part in 10^9	'97-'10
Laser gauges	• Commercial units insufficient • Some technology working in lab	Picometer accuracy	'97- '10
Components for Laser gauges: Modulators, Optical Fibers, Beamsplitters, Integrated Optics	Devices exist but not in spaceworthy form	TBD	'97-'10
Tunable Lasers for Absolute Laser gauging	Concept only.	300 GHz tuning range; 1 part in 10^9 accuracy of frequency markers	'97-'10
Endpoints (mechanical assemblies of optical components)	Concepts developed.	μm alignment of parts to be optically contacted or joined in other very stable way	'97-'10
Holographic Optical Elements (HOE)	• Concepts developed for metrology • Manufactured by industry for other applications	Uniform diffractive efficiency to 1%	'97-'10

Metrology (Cont'd)

- **Payoff / Performance:**

  Precise distance determination, which is necessary to convert the precision of an interferometer into accuracy; can be used as a sensor for CSI systems.

- **Existing Efforts:**

  Laser gauges are being developed at SAO (POINTS) and JPL (OSI).

- **Issues:**

  Need for absolute distance gauges (cf., incremental gauges like the HP laser gauge)

Fine Pointing with Isolation

HIGHLIGHTS

Reduced pointing error and vibration increase fringe visibility and coherence time, particularly in the POINTS configuration.

Supporting technologies included:

- **Inertial Reference**
- **Six-degree Suspension**
- **Control Structure Interaction (CSI)**

Fine Pointing with Isolation (Cont'd)

- **Objective:**
  - Maintain high fringe visibility and coherence time by reducing pointing error and vibration.

- **Applications / Missions Enabled:**
  - AIM (POINTS)

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
Inertial Reference	RMS noise (mas) in a band from 0.1 to 100 Hz • Gyros with field history : 3.5 • Gyros tested in lab: 0.7 • Angular diaplacement sensor: TBD (good performance above 1 Hz)	Better than 1 mas rms over 0.1 -100 Hz band	'97
Six-degree Suspension	Concept developed (e.g., by HDOS for SIRTF secondary mirror, rigid support)	Use force transducers, not displacement transducers	'97
CSI	Theory, concepts, initial laboratory work	TBD	'97

Fine Pointing with Isolation (Cont'd)

- **Payoff / Performance:**
  - Fringes can be made stable on an integrating detector; reduced detector read noise; reduced computational burden.
  - Effective isolation at fine-pointing suspension reduces need for other isolation of mechanically noisy components, such as reaction wheels.
  - The addition of a fine-pointing system eases the requirements of both the pointing gimbals and the S/C attitude control system.

- **Existing Efforts:**

  TBD

- **Issues:**

  For bright objects, fringes can be tracked in S/W with fast-read detectors. Astrometric information can be extracted from the fringe-tracking and metrology filter.

Active Delay Lines

HIGHLIGHTS

Active delay lines are required for making fringes in interferometers like OSI.

Supporting technologies included:

- Moving Carriage with Retroflector
- Optical Path Delay (OPD) Monitoring
- Vibration Suppression

Active Delay Lines (Cont'd)

- **Objective:**
  - Equalize path lengths of interferometer arms; suppress optical effects of structural vibrations.

- **Applications / Missions Enabled:**
  - AIM (OSI), II

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
Moving Carriage with Retroflector	Designs for ground-based interferometers	Lightweight, balanced actuators, low induced structural vibrations, 10 nm rms jitter	'97-'10
OPD Monitoring	(see metrology)	(see Metrology)	'97-'10
Vibration Suppression	TBD	Suppress structural vibrations to < 10 nm rms	'97-'10

Active Delay Lines (Cont'd)

- **Payoff / Performance:**
  - Required in order to make fringes in a class of interferometers.
  - Rapid precision delay lines permit quick retargetting and correspondingly high number of measurements per day.

- **Existing Efforts:**

  Ground-based interferometers in use and under development: JPL/USNO/SAO et al./etc.

  Infrared delay lines for space-based FTS.

- **Issues:**

  None.

Quiet Structures, Precision Deployment

HIGHLIGHTS

The extremely stringent stability requirements for astrophysics interferometry missions are met in part by minimizing spacecraft jitter, noise and vibration.

Technological approaches to these problems include the following:

- Microdynamics of Structures
- Passive and Active Damping
- Vibration Isolation
- CSI
- Deployable Precision Structures

Quiet Structures, Precision Deployment (Cont'd)

- **Objective:**
  - Develop and verify methods for designing structures and mechanical control systems that are stable and have a low level of mechanical noise; precise, post-launch deployment.

- **Applications / Missions Enabled:**
  - AIM, II, OVLBI-NG

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. Microdynamics of Structures	Preliminary investigations	Accurate modelling of structures at nanometer levels	'97-'10
2. Passive Damping, esp. @ low amplitude	Passive struts for reaction wheel isolation on HST	TBD	'97-'10
3. Active Damping	Concept only.	TBD	'97-'10
4. Vibration Isolation	TBD	x1000 suppression	'97-'10
5. CSI	Theoretical concepts.	Proven concepts, design methodology	'97-'10
6. Deployable Precision Structures	Deployment of camera, RTG booms on Voyager, Galileo	Reliable unfolding after launch of complex structures to within alignment servo capture, followed by locking of joints for rigidity (viz., will not creak, snap, buzz...)	'97-'10
		25-m deployable antenna, 30 μm rms surface accuracy (OVLBI-NG)	'02

Quiet Structures, Precision Deployment (Cont'd)

- **Payoff / Performance:**
  - Fringes visible only if vibration of OPD is small compared to an optical wavelength.
  - Reliable determination of fringe visibility, as required for interferometric imaging, requires vibration of OPD to be very small compared to an optical wavelength.
  - Higher ratio of performance to mass for structures: lower cost for large, high-performance structures.

- **Existing Efforts:**

  NASA CSI program for 1-5.

- **Issues:**

  None.

Materials and Structures for Stiff Optical Instruments

HIGHLIGHTS

- One way to reduce vibrational effects in interferometers is to support them with stiff optical structures, which stabilize the optical path.
- Another way is to use optical components that are light compared to mechanical support structures.

Materials and Structures for Stiff Optical Instruments (Cont'd)

- **Objective:**
  - Rigidly hold optical components

- **Applications / Missions Enabled:**
  - AIM, II

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. Lightweight Optical Components	TBD	TBD	'97-'10
2. Stiff Structures	TBD	TBD	'97-'10

Materials and Structures for Stiff Optical Instruments (Cont'd)

- **Payoff / Performance**:
  - Stiff optical structures maintain the OPD in an interferometer in the presence of mechanical disturbance, reducing the need for vibration-reduction techniques.

- **Existing Efforts**:
  - Development of lightweight optics.

- **Issues**:
  - Passive technology approach (e.g., increasing the ratio of structural mass to optical-component mass) vs. active technology approach (e.g., CSI).

Thermally Stable Optical Elements

HIGHLIGHTS

- Wavefront distortion can be reduced by fabricating optical elements from materials with low coefficients of thermal expansion.

- Materials for interferometric structures need high thermal conductivity for transmissive and reflective optics.

  -- minimizes the amount of heat absorbed

  -- minimizes structural distortion (thermal equilibrium rapidly attained)

Thermally Stable Optical Elements (Cont'd)

- **Objective:**
  - Minimize the wavefront distortion and OPD shifts associated with changes in temperature and temperature gradient.

- **Applications / Missions Enabled:**
  - AIM, II

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
1. Homogeneous and low CTE for mirror materials	ULE CTE of 2×10^{-9} /K for $(10\ cm)^3$ blocks claimed by Corning	TBD	'97-'10
2. Low D(1) for transmissive optics	TBD	TBD	'97-'10
3. High thermal conductivity for both transmissive and reflective optics	TBD	TBD	'97-'10

Note: (1) D = dn/dt + (n-1)*(CTE), where n is the refractive index, t is the time, and CTE is the coefficient of thermal expansion.

Thermally Stable Optical Elements (Cont'd)

- **Payoff / Performance:**

  Reduced sensitivity to thermal environment.

- **Existing Efforts:**

  TBD

- **Issues:**

  Lightweight optics frequently made with large voids, resulting in lower effective thermal conductivity and larger distortions from thermal gradients.

Interferometer Technology
Overall Priorities

HIGHEST:

- Metrology
- Fine Pointing with Isolation (POINTS)
- Active Delay Lines (OSI)
- Quiet Structures, Precision Deployment (OSI)

HIGHER:

- Materials and Structures for Stiff Optical Instruments (POINTS)
- Thermally Stable Optical Elements

HIGH:

- None

Observatory System Needs for Astrophysics

Presented to SSB/ASEB

June 24, 1992

David Skillman/GSFC

TECHNOLOGY/MISSION/REFERENCE MATRIX:

OBSERVATORY SYSTEMS

Briefing Topic	OSSA Chart Reference	Relevant Astrophysics (Code SZ) Missions	References
• Precision Instrument & Telescope Pointing	Precision Sensing Pointing & Control Low-drift Gyro's Trackers, Actuators	SIRTF, SMIM, ST-NG, AIM, IRST-NG	• No specific references - These charts were derived from on-going mission studies
• Lightweight, Longlife, Radiation-Tolerant Power Sources	Solar Arrays/Cells Batteries • Long lifetime • High energy density	All future Missions	
• Thermal Control Systems	Thermal Control System	SIRTF, AIM, LAGOS	
• Space Qualified Masers and Ion Clocks	Space Qualified Masers & Ion Clocks	OVLBI-NG	
• Ultra-High Gigabit/sec Telemetry	Ultra-High Gigabit/sec Telemetry	All future missions	
• K-band Transponders	K-band Transponders	AIM, II	
• Observatory Performance & Cost Modeling	None	SIRTF, AIM, other future observatories	
• Technologies for Low-Cost Missions	None	SmEx,UnEx	

Observatory Systems Technology Needs

- Includes
  - Pointing and control for future telescopes and instruments,
  - Power sources
  - Frequency standards
  - Telemetry systems and components
  - Thermal control systems and components
  - System level performance and cost models
- Many technology requirements are generic to most future missions. This includes requirements for power sources and telemetry as well as much of the technology for pointing and thermal control.
- Missions involving large optics, including interferometers and gravity physics missions, will be drivers for the precision required for pointing, thermal control and time/frequency measurement technologies

Precision Instrument & Telescope Pointing

(refer to under "Low-Drift Gyros, Trackers, and Actuators)

HIGHLIGHTS

- **Future IR and interferometry missions will require an improvement of two orders of magnitude over precision pointing capabilities available at present. Technological developments in the following areas will be necessary in order to achieve the capabilities needed:**
  - **Inertial Sensors/Gyros**
  - **Fine Guidance Sensing and Control**
  - **Star Trackers**
  - **Attitude, Solar Array and Antenna Actuation**
  - **Line-of-Sight Transfer**

Precision Instrument & Telescope Pointing (Cont.)

- **Objective:**
  - 100-fold increase over current precision pointing capabilities (i.e., control accuracy, stability, and knowledge) required by numerous astrophysics and other OSSA missions.

- **Applications / Missions Enabled:**
  - SIRTF, SMIM, AIM (OSI/POINTS), ST-NG, IRST-NG

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Inertial Sensors/Gyros	0.002 arc sec/s, 5 yr lifetime	Lower drift, longer life (>15 yrs., e.g., fiber optic gyro)	'97-'10
• Fine Guidance Sensing (FGS) & Control	Separate aperture, bright visible guide stars, 0.01 arc sec stability	0.1 arc sec cryo vis FGS (SIRTF, SMIM); 0.001 arc sec CCD FGS's (ST- NG)	'95-'97 '96-'04
• Star Trackers	1 arc sec, ground interpolated, no autonomy	0.1 arc sec CCD-based, autonomous; Feature tracking demonstration; Miniature scanners/wide FOV trackers	'96-'04 '97-'01 '95-'98
• Attitude Actuators	15 yr life; noise due to bearings, motor, rotor imbalance; 3 to 5 N-m-s/kg momentum per unit mass	Predictably longer life, quieter, higher momentum per unit mass (e.g., high-speed magnetic suspension)	'97-'04
• Appendage (Solar Array, Antenna) Actuation	Adequate accuracy, no momentum compensation	Integral high-bandwidth momentum compensation (DC - 100 Hz)	'99
• Line-of-Sight (LOS) Transfer (external tracker to focal plane)	Concept only	0.1 arc sec cryo (2 K) prototype (SIRTF, SMIM)	'95-'97

Precision Instrument & Telescope Pointing (Cont.)

- **Payoff / Performance:**
  - Increase reliability, lifetime, and efficiency of pointing hardware
    - 3-fold improvement of reliability and life of critical components (gyros, star trackers, reaction wheels, etc.)
  - Enables precision pointing performance for all future telescope missions
    - 10-fold improvement in precision beyond HST
    - New capabilities for FGS, LOS transfer, telescope nodding and interferometer multi-aperture pointing
  - Increase remote sensing instrument pointing capability by 2 orders of magnitude
    - 100-fold improvement in precision over current LEO state-of-the-art
    - Increased science throughput/operational efficiency via on-board pointing automation
    - Provide new capabilities in target referenced pointing, attitude transfer, and multi-spectral instrument co-boresighting

- **Existing Efforts:**
  - Fiber Optic Rotation Sensor (FORS), a joint effort of NASA Codes R, S, and Q, to deliver better than 0.001 arcsec/s Single-Axis Engineering Mode by October 1992. Expected lifetime 15 years.
  - All-sky autonomous star identification proof-of-concept demonstration by Code R, Sept. 1992.

- **Issues:**
  - FY93 continuity of FORS long life gyro program to deliver first 4-axis flight IRU. Will need multi-code and multi-user support.
  - FY95 technology readiness need date for SIRTF requires FY93 start on technology development (60 K, 0.1 arc sec external FGS, and 2 K LOS transfer and calibration system).

Lightweight, Longlife, Radiation-Tolerant Power Sources

HIGHLIGHTS

- **Future astrophysics missions will require reliable, lightweight power sources and storage devices capable of delivering sustained electric power for many years (>15).**
- **Improvements to existing solar-array and battery designs will be made in parallel with development of alternative long-life generators, such as Radioisotope Thermoelectric Generators (RTGs), particularly useful during lunar night or long space flights far from the Sun.**

Lightweight, Longlife, Radiation-Tolerant Power Sources (cont.)

- **Objective:**
  - Develop significantly improved solar power arrays, energy storage, RTGs, power conversion devices.
- **Applications / Missions Enhanced:**
  - All Missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• High Specific Energy Solar Power Array	Silicon 35-40 W/kg, 130-150 W/m^2 GaAs/Ge 35-40 W/kg, 180 W/m^2 Design Life 5-7 years	~200 W/kg 10-15 years	'96
• Secondary Storage Batteries			
•• Ni-Cd	32 WH/kg, 5000 cycles	~100 WH/kg	'96
•• $Ni-H_2$	50WH/kg, 5000 cycles	~150 WH/kg	'00
• RTGs	5.4 W/kg	~8-10W/kg	'00
• Power Devices	Volume = 1.0 Mass=1.0	Volume = 0.6 to 0.3 Mass=0.6	'96

Lightweight, Longlife, Radiation-Tolerant Power Sources (cont.)

- **Payoff / Performance:**

  The power subsystem is basic to all missions. Improvements in power systems technology result in lower mass associated with the system and the S/C.

- **Existing Efforts:**

  OAST is currently funding the development of improved solar arrays and batteries. DoE also has an active battery program, primarily for ground-based applications. NASA activities in Advanced Photovoltaic Solar Array (APSA) and Advanced Thermoelectric Materials (for RTGs) are being funded by OAST. Battery development is also being funded by DoD (Li-TiS_2).

- **Issues:**

  Improvements in power systems technologies have the potential to substantially reduce the mass -- and thus the cost -- associated with the S/C. Long-term missions and others such as Lunar Transit Telescope (LTT) have no option besides RTGs. Currently, RTGs are large and high-powered (300 W). There is considerable interest in developing 40-80 W RTGs.

Thermal Control Systems

HIGHLIGHTS

- Precision measurements -- particularly IR, interferometry, and gravity-wave measurements -- require that noise, vibration, and distortions due to thermal gradients be minimized. This will involve:
  - cooling sensors actively to subkelvin temperatures
  - monitoring their temperature
  - removing or reducing heat by passive means, such as optical heat pipes.

Thermal Control Systems (Cont.)

- **Objective:**
  - Develop technology and methods to monitor and control temperature of critical elements of space-based telescopes and interferometers. Future missions will require extremely tight control of temperature fluctuations associated with optics and structures.

- **Applications / Missions Enabled:**
  - SIRTF, SMIM, AIM, LAGOS

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Temperature Sensing Technology	Thermistors (Voyager, Galileo, Mars Observer) ± 30 mK	1 - 5 mK	'96
• Temperature Control Technology	Electronic Thermostats ± 100 mK	± 10 mK	'96
• Low-Temp. (<1K) Sensor Cooling	LHe Dewar	ADR & 3He/4He Dilution Refrig.	'96
• Optical Heat Pipe for Heat Transfer	Heat Conductive & Mass Transfer	Up to 15 W @ 250-270 K	'97
• Optical Path & Accelerometer Cavity Stability (LAGOS)	Concept Only	0.1 mK/(√Hz) under IMOS Program	'98

Thermal Control Systems (Cont.)

- **Payoff / Performance:**

  Performance of SIRTF and AIM (OSI) is largely tied to the thermal control system.

  Platinum resistance and test thermocouples are promising as accurate sensors of absolute temperature.

  Thermistors are good candidates for accurate sensing of temperature differences/gradients.

  Heat pipes are being studied for use in the passive cooling of observatories, as well as for thermal transport.

  Subkelvin coolers are needed for sensitive sensors on advanced missions.

- **Existing Efforts:**

  There are no known concerted efforts for generic R&D on precision temperature sensing and control systems for space instrument applications, nor any for optical heat pipes. Recent efforts have been directed to specific instruments at project level, e.g., HST instruments, lambda-point experiments, etc.

- **Issues:**

  Advances in technology are needed to enable missions requiring stable thermal sensing and control. Although dimensional stability of critical components and structural elements is a key issue, thermal problems are also of great importance. NASA support for subkelvin coolers, never strong, has grown weaker.

Space-Qualified Masers and Ion Clocks

HIGHLIGHTS

- **OVLBI, Gravity-Wave and General Relativity missions can use cryogenic maser and trapped-ion clocks as metrology and calibration standards, eliminating the need for communication with ground-based clocks.**
- **Although cryogenic devices of sufficient stability and lifetime operate in ground-based laboratories, development of space-qualified models is still required.**

Space-Qualified Masers and Ion Clocks (cont.)

- **Objective:**
  - Development of stable, space qualified cryogenic maser and trapped-ion clocks for use as metrology and calibration standards, particularly for OVLBI systems, which require precision clocks to determine spacetime coordinates of spacecraft in a given system.

- **Applications / Missions Enabled:**
  - OVLBI-NG, Future Relativity Experiments

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Frequency-Stabilized Space-Qualified Hydrogen Maser for EURECA Experiment	Stability of $\leq 1{:}10^{15}$ for intervals between 10^3 and 10^5 sec in terrestrial applications	Stability of $\leq 1{:}10^{15}$ for intervals between 10^3 and 10^5 sec in space applications	'94
• Improved Cryogenic Storage of Atomic Hydrogen for Long-Term Operation in Space	Laboratory operation at 0.5 K using a closed-cycle ^3He cryostat	Operation in space in the milli-Kelvin range using a dilution refrigerator	'94
• Space-Qualified Trapped-Ion Clock	Laboratory demonstration of stability of ~ $1{:}3 \times 10^{16}$ for intervals $>10^4$ sec	Demonstration of space-qualified H/W	'97

Space-Qualified Masers and Ion Clocks (cont.)

- **Payoff / Performance:**

  On-board clocks can be used to determine the distances between component spacecraft of an orbiting interferometry system without reference to ground-based clocks. They can also serve as frequency standards for precise calibration of spacecraft instruments, and for measuring exceedingly small frequency shifts and time intervals characteristic of experimental tests of General Relativity Theory, esp. gravitational radiation and relativistic gravity.

- **Existing Efforts:**

  Principal space-worthy cryogenic hydrogen maser development effort is being carried out at SAO with Code R support. It is to be tested on the ESA EURECA spacecraft in 1995. Trapped-ion devices are being developed at JPL.

- **Issues:**

  Maser devices have been used in space since 1976. Current issues include: development of space-qualified cryogenic systems, reduction of environmental effects on stability, and reduction of cost. Trapped ion devices currently being developed are less expensive, less vulnerable to adverse environmental destabilization, and much less massive.

Ultra-High Gigabit/Second Telemetry (cont.)

HIGHLIGHTS

- OVLBI and other large-scale interferometry missions will require wide band-width optical and RF telemetry that represents an order of magnitude improvement over the 300 Mb/s data rate currently used by TDRSS/DSN.
- Real-time interactive instrument control would greatly improve the operation of multi-beam phased arrays or analogous optical systems that receive simultaneous input from multiple instrument sites.

Ultra-High Gigabit/Second Telemetry (cont.)

- **Objective:**
  - Develop very wide bandwidth ($\geq$3 Gb/s continuous) space-to-space and space-to-ground telemetry links, a system to continuously obtain data from multiple instruments, and a capacity for real-time, interactive control of some instruments by ground-based investigators.

- **Applications / Missions Enabled:**
  - OVLBI-NG, II

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Optical & RF Telemetry Links with Continuous Multi-Gb/s Capacity, Both Space-Space & Space-Ground	TDRSS/DSN (300 Mb/s)	1 - 10 Gb/s	'97-'98
• Multi-beam Phased Array Antennas or Multi-aperture Optical Systems to Obtain Data from Multiple Instrument Sites Simultaneously	VLBA, Mark III No real-time interactive control	Real-time interactive instrument control	'97-'98

Ultra-High Gigabit/Second Telemetry (cont.)

- **Payoff / Performance:**

  Required for communicating between elements of future interferometry missions, such as OVLBI-NG. Provides needed data rate for future instrumentation employing large (> 10^6) detector arrays, and for ground, real-time, interactive control of some instruments.

- **Existing Efforts:**

  The OAST is funding development of a number of high-rate, large-capacity data processing systems under the CSTI program, including real-time, ground-based and on-board types of units. Code O is also funding development of optical Ka-Band communications for telemetry purposes.

- **Issues:**

  These are generic technologies which can be used by missions generating or downlinking data at high rates, and require real-time interactive control.

K-Band Transponders

HIGHLIGHTS

- The use of high frequency K-band transponders (ideally as high as 80 GHz) in future astrophysics missions is very desirable in the long run, particularly for OVLBI and other interferometry missions requiring very high data rates.
  - International frequency-allocation conventions will require operation in that band.
  - K-band operation offers wider bandwidth and lower noise than at currently used frequencies.
  - NASA is already developing Ka-band tracking support for VSOP.

K-Band Transponders (cont.)

- **Objective:**
  - Develop K-band (40-50 GHz) transponders to be used in future spacecraft, to conform to international frequency-allocation conventions, and to take advantage of greater bandwidth and reduced noise at these frequencies.

- **Applications / Missions Enabled:**
  - OVLBI-NG, II

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Space-Qualified K-Band Transponders & K-Band Ground-Support Systems	Ka-Band (22.5-27.5 GHz) Ground Network being constructed in support of VSOP mission	100 MHz bandwidth @ 40-50 GHz for telemetry (ultimately ~80 GHz)	'97 - '05

K-Band Transponders (cont.)

- **Payoff / Performance:**

  K-band telemetry will conform to international frequency allocations, based on limited spectral availability in currently used bands. K-band permits the 100 MHz bandwidth required for future telemetry. Furthermore, this band is relatively immune to plasma and ionospheric interference, which fall off with increasing frequency.

- **Existing Efforts:**

  NASA is committed to provide Ka-band ground support, tracking, and data capture for the Japanese VSOP (space VLBI) mission. Japan is already developing Ka-band S/C transponders for this mission.

- **Issues:**

  Given the Japanese lead in technology development in this band, and the advantages and ultimate necessity of K-band telemetry, the US should extend its ground-support development to include on-board technology as well, while the field is still open to competition.

Observatory Performance & Cost Modeling

HIGHLIGHTS

- To reduce costly errors in observatory planning, a detailed, flexible "bang-for-buck" model is required that will calculate tradeoffs between the science requirements and budgetary constraints for different mission scenarios.

Observatory Performance & Cost Modeling (Cont.)

- **Objective:**
  - •• Develop a model to conduct performance/cost tradeoff studies for observatory missions.
- **Applications / Missions Enabled:**
  - •• All Observatories

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
Model allowing performance/design tradeoff studies to be conducted in early phases of the project	Design decisions are based on experience and philosophy minimizing risk. Tradeoff studies do not always account for operations costs. IMOS currently addresses only performance.	Performance/design tradeoff studies based on life-cycle costs for observatories	'95

Observatory Performance & Cost Modeling (Cont.)

- **Payoff / Performance:**

  Most critical decisions are made in the early phases of a project when the resources for detailed studies are tight. Availability of a model that allows the tradeoff between the science requirements and costs will result in realistic expectations of science return early in the project development. The model is based on S/C resource allocation, resource cross-consumption, subsystem cost and performance database, and operations cost. The model will build on IMOS capabilities and add a cost module.

- **Existing Efforts:**

  The Subsystem Design Tradeoff Model (SDTM) was developed at JPL for performing these trade studies for Space Station. IMOS has already integrated several of the key performance parameters.

- **Issues:**

  Cost will be a major design parameter for most of the future missions. The use of the model results in efficient allocation of resources, and optimizes the science returns. The model also helps to pinpoint the allocation of technology development activities early in the program. Use of the model does not require a cultural change, but formalizes the need for an efficient decision-making process.

Technologies for Low-Cost Missions

HIGHLIGHTS

- Smaller-scale missions using off-the-shelf, microminiature spacecraft components could provide an inexpensive avenue to astrophysical observation with a short lead time.

- Astrophysics observatory designers may be able to take advantage of the approach used by SDIO for "Brilliant Pebbles"

- Both production techniques and the components produced may have broader applications in industry.

Technologies for Low-Cost Missions (cont.)

- **Objective:**
  - Develop subsystem components for use in low-cost astrophysics missions.
- **Applications / Missions Enabled/Enhanced:**
  - SmEx and UnEx missions, possible future on-board or lunar applications

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Miniaturization of Existing Components	TDRSS transponders, gyros, star trackers, and power systems too massive for small, low-cost missions	Reduction of mass of transponders, gyros, star trackers, RTGs, etc., by a factor of 2 to 3	'96
• Microminiature Technologies	Some micromechanical devices fabricated out of silicon; electronic components, microprocessors and memory chips being reduced in size for ground-based applications	Novel devices for spacecraft applications are under study, and will be tested and used as they are developed; most exist only as concepts at present.	TBD

Technologies for Low-Cost Missions (cont.)

- **Payoff / Performance:**

  There is growing interest within NASA in complementing the Great Observatory program with more frequent, smaller-scale missions ($60M-$150M). The availability of off-the-shelf spacecraft components for such programs would reduce both overall cost and production time, particularly if such components could be produced and used in sufficient numbers. In addition, current small missions frequently cannot use existing components -- e.g., SAMPEX must use the Wallops facility because TDRSS transponders are too heavy for SmEx S/C (17 kg vs. the required ~6 kg). Development of microminiature components, currently under study for Mars Rovers and similar projects, could have applications in robotics and other potentially commercial technologies, as well as for on-board robotics or lunar-surface operations.

- **Existing Efforts:**

  NSF has a small program addressing micromechanical device technology. JPL has initiated a program for microdevices funded by DARPA. SDIO's "Brilliant Pebbles" approach successfully applies miniaturization concepts which may provide a model for small astrophysics missions.

- **Issues:**

  Microtechnologies appear promising for use in future missions. Prototypes currently being developed are not only lightweight but easy to fabricate. However, the development of miniaturized versions (1/2 to 1/3 current mass) of existing components, which would considerably benefit smaller astrophysics missions currently under consideration, has not been adequately addressed.

Observatory Systems Overall Priorities

HIGHEST:

- Precision Instrument & Telescope Pointing
- Space Qualified Masers and Ion Clocks

HIGHER:

- Lightweight, Longlife, Radiation-Tolerant Power Sources
- Thermal Control Systems

HIGH:

- Ultra-High Gigabit/sec Telemetry
- Technologies for Low-Cost Missions
- K-band Transponders
- Observatory Performance & Cost Modeling

Information Technology Needs for Astrophysics

Presentation to SSB/ASEB

June 24, 1992

Dr. Rodger Doxsey/STScI

TECHNOLOGY/MISSION/REFERENCE MATRIX:

INFORMATION TECHNOLOGY

Briefing Topic	OSSA Chart Reference	Relevant Astrophysics (Code SZ) Missions	References
• On-Board Data Compression, Image Processing & Data Storage	On-board Storage & Compression	All future missions	• No specific reference- These charts were derived from unpublished data from the AT 21 Workshop on Information Systems
• Observation Planning and Sequencing Tools	None	SIRTF, other future missions	
• Ground-based Data Processing	Data: • High Volume, High Density, High Data Rate	All future missions	
• Data Visualization and Analysis	Parallel Software Environment for Model & Data Assimilation, Visualization	All future missions	
• (Withdrawn)	3-D Packaging for 1 MByte Solid State Chips		

Information Systems Technology Needs

- Primarily generic and much of what is needed is expected to evolve from the industrial base for commercial products.
- Improvements needed in
  - On-board processing,
  - Ground data processing and display
  - Operations/Mission Planning
- Software is often unique including software used for simulation, modeling and data processing
  - Software cross-fertilization between space science disciplines is limited and would be beneficial

On-board Data Compression, Image Processing, And Data Storage

HIGHLIGHTS

- Fast data compression processors for spectral and image data (to 100:1)
- Pre-processing detector output for OBC compression
- Solid-state recorder development to store 4-20 GBytes

On-board Data Compression, Image Processing, And Data Storage (cont.)

- **Objective:**
  - Develop pre-processing algorithms and practical implementation schema to enable use of data compression chips developed in the OAST program.

- **Applications / Missions Enhanced:**
  - All Missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Fast data compression processors for spectral & image data	2:1-8:1, depending on data type	Compression ratio up to 100:1	'94 - '97
• Pre-processing detector output	Adaptive compression algorithm for OAST-funded prototype flight chip development	Practical implementation of compression and image processing by appropriate on-board computer	'92 - '98
• Solid State Recorder (SSR)	Tape recorder	Requirements vary: 4-20 GBytes	'96

On-board Data Compression, Image Processing, And Data Storage (cont.)

- **Payoff / Performance:**

  Compression is required by S/C baseline telecommunications design to enable use of the highest desired data rates for SIRTF and AXAF II. Pixel-to-pixel characteristics of data must be made compatible with established data compression algorithms, using appropriate pre-processing of raw detector data prior to compression. Solid State Recorders are inherently more reliable. 3D packaging (surface mount) with SRAM chips results in low volume and power requirements.

- **Existing Efforts:**

  JPL, GSFC, and the University of Idaho are involved in developing chip prototypes and data compression algorithms, funded by OAST. OAST is also supporting the development of surface mount technology for packaging of the RAM chips.

- **Issues:**

  Onboard processors have traditionally lagged in terms of technology behind their ground-based counterparts. A major advantage of these chips is that they weigh less and consume relatively less power. SSRs are more reliable and do not impose any induced loads on ACS due to rotating masses. Data compression on board the S/C results in doubling the science return for a 2:1 compression.

Observation Planning And Sequencing Tools

HIGHLIGHTS

- S/W model of observatory pointing and instrument operational modes
  - integrated with prototype observation planning work station
  - driving prototype sequence planner
- Scenarios for adaptive sequencing and onboard command generation
  - corresponding ground sequence planning and verification system requirements

Observation Planning And Sequencing Tools (cont.)

- **Objective:**
  - Demonstrate potential benefits of expert systems and other advanced techniques in observation planning and sequence generation process for a space observatory. Develop and verify schema for adaptive sequencing of observations by an observatory mission which increases the efficiency of observation execution and decreases loss of observing time.

- **Applications / Missions Enabled:**
  - All Missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• S/W model of observatory pointing and instrument operational modes, integrated with prototype observation planning work station, driving prototype sequence planner	Concept only	Integrated Model	'94
• Mission-specific candidate scenarios for adaptive sequencing, and corresponding flight system and ground sequence planning and verification system requirements	Sequences are deterministic and pre-planned	Adaptive sequencing, automated generation of commands	'94

Observation Planning And Sequencing Tools (cont.)

- **Payoff / Performance:**

  Observation planning and sequence-generation tools are necessary to maximize efficient utilization of observatory resources. Appropriate prototype systems must be established and translated into design requirements prior to development of the flight system. These systems have the potential to significantly lower the cost of operations.

- **Existing Efforts:**

  This is a relatively new approach to the sequencing process. Some autonomous missions, such as the Mars Rover, are considering this technology.

- **Issues:**

  The use of these models requires a significant change in operations philosophy. Adaptive sequencing is being considered for SIRTF; if successful, it can provide a basis for operations which will have a major impact on reducing operations costs for follow-on missions.

Data Visualization And Analysis

HIGHLIGHTS

- Portable, user-friendly S/W
  - for rapid retrieval, exchange, visualization, and interactive analysis of multidimensional data

- Standards for data file and exchange formats
  - for easy correlation and analysis of data from multiple archives

Data Visualization And Analysis (cont.)

- **Objective:**
  - Develop portable, interactive computer software to allow the most productive analysis and visualization of large quantities of data; data standards to allow scientists to access data from multiple sources and combine data from multiple instruments and missions; and intelligent interfaces for visualization and analysis of multi-dimensional data.

- **Applications / Missions Enabled:**
  - All Missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Portable, User-friendly Software for Rapid Retrieval, Exchange, Visualization, and Interactive Analysis of Multidimensional Data.	"Explorer" and "Linkwinds"-- Interactive Multi-dimensional Data Analysis & Visualization, work only on SGI Workstations	Truly portable software working on many platforms	'98
• Standards (Development And Usage) for Data File Formats and Data Exchange Formats to Allow Easy Correlation and Analysis of Data from Multiple Archives	0.7 Gbytes (Input Data) 1/60 Frame/Sec User-specified Parameters for Key-frame Based Animations	Develop standards for data interchange on several platforms	'98

Data Visualization And Analysis (cont.)

- **Payoff / Performance:**

  Only a small fraction of data from space missions has been analyzed. Availability of tools for rapid prototyping of visual data analysis is needed. Powerful workstations make this possible.

- **Existing Efforts:**

  Code SMI is currently funding "Linkwind" development at JPL. OAST has initiated a program to address visualization.

- **Issues:**

  The software development approach should consider making visualization user-friendly and truly portable, to allow interchange of data from a variety of sources. Development of flexible, multidimensional presentation and animation packages for personal computers would also be welcome.

Ground-based Data Processing

HIGHLIGHTS

- Faster (multi-Tflops) and more efficient general purpose computers
- High-speed (better than 1 Gb/s) ground networks
- On-line mass data storage systems
  - for easy data exchange between multi-TByte systems

Ground-based Data Processing (cont.)

- **Objective:**
  - Develop high performance teraflop computing capability, wide-bandwidth ground data links to users at widely scattered sites, and large, rapidly accessible data archiving and retrieval systems to support on-line access to multi-terabyte databases.
- **Applications / Missions Enabled:**
  - All Missions

Required Technology	Current State of the Art	Science Mission Requirement	Date Needed
• Faster and More Efficient General Purpose Computers (Multi-Tflop)	1.2 GFlops	Higher processing speeds (~10x)	'98 - '00
• High Speed Ground Networks ($\geq$ ~1 Gb/s)	100 Mb/s	Higher data rates (~10x)	'98 - '00
• On-line Mass Data Storage Systems to Allow Easy Exchange of Data between Multi-TBytes Systems	10^{10} Bytes	Higher storage capacities (~10x)	'98 - '00

Ground-based Data Processing (cont.)

- **Payoff / Performance:**

  This effort benefits substantially from developments in the commercial environment. Higher processing speeds will open up avenues for a variety of applications.

- **Existing Efforts:**

  Parallel software environment consisting of both H/W and S/W is currently being funded by NSF.

- **Issues:**

  Higher processing and data rates provide substantial benefits to researchers and the science community at large.

Information Technology
Overall Priorities

HIGHEST:

- **On-Board Data Compression, Image Processing & Data Storage**
- **Data Visualization and Analysis**

HIGHER:

- **Ground-based Data Processing**

HIGH:

- **Observation Planning and Sequencing Tools**

Astrophysics Technology Development Needs Presentation: Acronyms & Abbreviations

Missions and Instruments:

ACT	Advanced Compton Telescope (balloon instrument)
AIM	Astrometric Interferometer Mission
AXAF	Advanced X-ray Astrophysics Facility
AXAF	Advanced X-ray Astrophysics Facility, Second Generation Instruments
COBE	Cosmic Background Explorer
EOS	Earth-Observing System
EURECA	European Retrievable Carrier (ESA Space Shuttle payload)
FUSE	Far Ultraviolet Spectroscopic Explorer
GP-B	Gravity Probe-B
GRO	Compton Gamma-Ray Observatory
GRSO	Gamma-Ray Spectroscopy Facility
HST	Hubble Space Telescope
HXIF	Hard X-ray Imaging Facility
II	Imaging Interferometer
Integral	International Gamma Ray Laboratory (see NAE)
IRAS	Infrared Astronomy Satellite
IRST-NG	Infrared Space Telescope - Next Generation (a.k.a. LDR)
KAO	Kuiper Airborne Observatory
LAGOS	Laser Gravitational-wave Observatory in Space
LDR	Large Deployable Reflector
LTT	Lunar Transit Telescope
Mark III	Mt. Wilson Interferometer
NAE	Nuclear Astrophysics Experiment (NASA's alternative to ESA's Integral)
-NG	Next Generation
ORI	Orbital Replacement Instrument (HST)
OSI	Orbiting Space Interferometer (AIM)
OVLBI-NG	Orbiting Very Long Baseline Interferometry - Next Generation
POINTS	Precision Orbiting Interferometer in Space (AIM)
Radioastron	Russian (formerly Soviet) OVLBI mission
SIRTF	Space Infrared Telescope Facility
SMIM	Submillimeter Intermediate Mission
SMMI	Submillimeter Interferometer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SSPM	Solid-State Photomultiplier
ST-NG	Space Telescope - Next Generation
STIS	Space telescope Imaging Spectrograph (HST)
STIS II	Second-Generation STIS Instrument
UARS	Upper Atmosphere Research satellite
UARS/MLS	Microwave Limb Sounder on UARS
VLBA	Very Long Baseline Array
VHTF	Very High Throughput Facility
VLT	ESA's Very Large Telescope
VSOP	Japanese OVLBI mission
WF/PC (1,2)	Wide-Field Planetary Camera (HST)
WFXT	Wide-Field X-ray Telescope (USA/Italy)
XMM	X-ray Multi-mirror Mission (ESA)
XST	X-ray Schmidt Telescope

General:

1D, 1-D	1-Dimensional
2D, 2-D	2-Dimensional
3D, 3-D	3-Dimensional
@	[at]
Å	Angstrom Unit (= 10^{-10} meters)
AASC	Astronomy & Astrophysics Survey ("Bahcall") Committee (of NAS)
ACS	Attitude Control System
A/D	Analog-to-digital [converter/conversion]
ADR	Adiabatic Demagnetization Refrigerator
Adv.	Advanced
AGN	Active Galactic Nucleus/Nuclei
Align.	Alignment
anal.	Analysis
ang. res.	Angular Resolution
AO	NASA Announcement of Opportunity
AOS	Acousto-optic Spectrometer
APSA	Advanced Photovoltaic Solar Array
ARC	NASA/Ames Research Center
arc min	Arcminute
as, arc sec	Arcsecond
AT21	Astrotech 21, Astrophysics Technology for the 21st Century
ATD	Advanced Technology Development
ATM	Advanced Thermoelectric Materials
Be	Beryllium
B/G	Background
BIB	Blocked Impurity-Band (see IBC)
BRDF	Bidirectional Reflectance Distribution Function
BW	Bandwidth
CCD	Charge-coupled Device
CID	Charge-injection Device
Code O	NASA's Office of Space Operations
Code Q	NASA's Office of Safety and Mission Quality
Code R	See OAST
Code S	See OSSA
Code SMI	Part of OSSA's Flight Systems Division
Code SZ	OSSA's Astrophysics Division
Cont'd, Cont.	Continued
Cryo	Cryogenic
CSI	Controls-Structures Interaction
CSTI	NASA's Civilian Space Technology Initiative
CTE	Coefficient of Thermal Expansion
ctrs	Counters
cts	Counts
cts/ch-sec	Counts per Channel per Second
CVD	Chemical Vapor Deposition
D	[Time-Variation of Refractive Index]
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current (0 Hz)
Degrad.	Degradation
demo	Demonstration
DoD	Department of Defense

DoE	Department of Energy
DOF	Degree[s] of Freedom
DSN	Deep Space Network
eV	Electron Volt
E/ΔE	Energy Resolution (Signal/Bandwidth)
ELV	Expendable Launch Vehicle (i.e., a rocket)
E/M	Electromagnetic
ESA	European Space Agency
EUV	Extreme Ultraviolet
fab.	Fabrication
FET	Field-Effect Transistor
FGS	Fine Guidance Sensing
fig.	Figure
FORS	Fiber Optic Rotation Sensor
FOV	Field of View
FPA	Focal-plane array
freq	Frequency
FTS	Flight Telerobotic Service
FY	Fiscal Year
GaAs	Gallium Arsenide
GBytes	Gigabytes (data storage)
Ge	Germanium
Ge:Ga	Gallium-doped Germanium
Gflops	Gigaflop = 10^9 Floating Point Operations per Second
GHz	Gigahertz (10^9 Hertz or cycles/second)
Gr/Ep	Graphite/Epoxy
GSFC	NASA/Goddard Space Flight Center
HDOS	Hughes Danbury Optical Systems (formerly, Perkin-Elmer)
He-3, ^{3}He	Helium-3
^{4}He	Helium-4
HEA	High-Energy Astrophysics
HeNe	Helium-Neon [Laser]
HgCdTe	Mercury-Cadmium-Telluride
hi	High
hν/k	[Frequency expressed in temperature units]
HOE	Holographic Optical Element
HP	Hewlett-Packard
H/W	Hardware
HXR	Hard X-ray
Hz	Hertz (cycles/second)
IBC	Impurity-Band Conduction (a.k.a. BIB)
IDEA	Initiative to Develop Education through Astronomy
IMOS	Integrated Modeling of Optical Systems (JPL)
Init.	Initialization
IRU	Inertial Reference Unit
ISM	Integrated System Modeling
JPL	Jet Propulsion Laboratory
K	[Degrees] Kelvin
k	Kilo-, x 1000
Ka-Band	22.5-27.5 GHz
keV	Kilo Electron Volts (= 1000 eV)
kHz	Kilohertz (= 1000 Hertz or cycles/second)
kW	Kilowatt

λ	Wavelength
LEO	Low Earth Orbit
LHe	Liquid Helium (@ temperature of 4 K)
Li-TiS_2	Lithium-Titanium Sulfide (battery)
LN_2	Liquid Nitrogen (@ temperature of 77 K)
LO	Local Oscillator
LOS	Line of Sight
mas	Milliarcsecond
max	Maximum
MByte	Megabyte (= 10^6 bytes, data storage capacity)
Mb/s	Megabits/second (= 10^6 bits/second, data rate)
MCP	Microchannel Plate
MCT	Mercury-Cadmium-Telluride
Meas.	Measurement
mech/chem	Mechanical/Chemical
MeV	Million Electron Volts
MHz	Megahertz (= 10^6 Hertz or cycles/second)
MidEx	"Middle-Class" Explorer[s]
MIPS	Million Instructions per Second (processor)
mK	Millikelvin (= 10^{-6} degree Kelvin)
mK/$\sqrt{\text{Hz}}$	Millikelvin per root hertz
MO&DA	Mission Operations and Data Analysis
MODIL	SDIO's Manufacturing Operations, Development and Integration Laboratory
MOS	Metal-oxide-semiconductor
MSFC	NASA/Marshall Space Flight Center
mW	Milliwatt (= 10^{-3} watt)
MWIR	Microwave and Infrared
μ	Micro-, 1 millionth; very fine-scale
μas	Microarcsecond
μm	Micron (= 1 micrometer, 10^{-6} meter)
μW	Microwatt (= 10^{-6} watt)
NAR	Non-Advocate Review
NAS	National Academy of Sciences
Ni-Cd	Nickel Cadmium
Ni-H_2	Nickel Hydride
nm	Nanometer (= 10^{-9} meter)
N-m-s/kg	Newton-Meter-Second per Kilogram (angular momentum per unit mass)
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
NTT	New Technology Telescope (European Southern Observatory)
OAST	Office of Aeronautics and Space Technology (NASA's Code R)
obs.	Observation
OPD	Optical Path Delay
OSSA	Office of Space Science and Applications (NASA's Code S)
PACE	Plasma Assisted Chemical Etching
PI	Principal Investigator
pm	Picometer (= 10^{-12} meter)
prob	Probably
prog	Program
PSR	Precision Segmented Reflector
PV	Photovoltaic

p-v	Peak-to-Valley (surface figure measure)
QE	Quantum Efficiency
R&D	Research and Development
RADC	Rome Air Force Development Center
RAM	Random Access Memory
Rec.	Receiver
refrig	Refrigerator
Res.	Resolution
RF	Radio Frequency
ROC	Radius of Curvature
rms	Root Mean Square
RTG	Radioisotope Thermoelectric Generator
s, sec	Second
SAO	Harvard-Smithsonian Astrophysical Observatory
S/C	Spacecraft
SDI[O]	Strategic Defense Initiative [Organization]
SDTM	Subsystem Design Tradeoff Model (JPL)
seg.	Segmented
sens.	Sensing
SGI	[brand-name of computer workstation]
Si	Silicon
Si:As	Arsenic-doped Silicon
SiC	Silicon Carbide
SIS	Superconductor-insulator-superconductor
Si:xx	Doped silicon
SmEx	Small Explorer[s]
SRAM	Static Random Access Memory
SSAAC	Space Science and Applications Advisory Committee (for OSSA)
SSB/ASEB	Space Studies Board/Aeronautics and Space Engineering Board (NAS)
SSR	Solid-state Recorder
STScI	Space Telescope Science Institute
Submm	Submillimeter
S/W	Software
T	Temperature
TBD	To Be Determined/Decided/Done
TByte	Terabyte = 10^{12} Bytes [of data storage]
TDRSS	Tracking and Data Relay Satellite System
Tech	Technology, Technique
Technol.	Technology
Temp	Temperature
Tflops	Teraflop = 10^{12} Floating Point Operations per Second
THz	Terahertz (10^{12} Hertz or cycles/second)
Trans	Transmissivity, Transmission
ULE	Ultra Low Expansion glass, made by Corning
UnEx	University Small Explorer[s]
USNO	United States Naval Observatory
UV	Ultraviolet
VIS, Vis	Visible Light, Optical
W	Watt
WH/kg	Watt-Hours per Kilogram
Xe	Xenon

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